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CORRECTION

Monthly Weather Review, April 1951, vol. 79, No. 4, Charts XIV and XV: The red overlays of temperature on these two maps should be interchanged.

DEPARTMENT OF COMMERCE
CHARLES SAWYER, Secretary

WEATHER BUREAU
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ON THUNDERSTORM FORECASTING IN THE CENTRAL UNITED STATES

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ABSTRACT

This study is directed toward a better understanding of the occurrence and forecasting of thunderstorms as an element of general weather patterns or sequences of patterns. The principal area studied is the Central United States. Following a review of the literature, the climatology of thunderstorms is examined. Then, from an analysis of many thunderstorm situations, the typical features and important synoptic patterns of areas of thunderstorm activity and their movement and life cycle are described. Finally some of the parameters suggested by the study are incorporated into a systematic technique to aid in the preparation of forecasts of thunderstorms during a 24-hour period at Chicago. The procedure is based upon 850-mb. chart types, previous occurrence of thunderstorms, and moisture and stability. A test on independent data gives good results.

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INTRODUCTION

The forecasting of thunderstorms has been named by many forecasters as an unusually difficult problem deserving of some special research attention. About 100 persons have lost their lives in airplane accidents in thunderstorms in the Midwest within the last few years. Attempts at forecast improvements are justified by widespread interest in this difficult problem and by possible savings of lives and of property that may be realized through the proper use of good thunderstorm forecasts.

Despite the need for improved techniques, relatively few specific thunderstorm forecast relationships have been enunciated, aside from the classical thermodynamic analyses. Willett [1] discussed two basic factors that have become widely used. The first factor is the depth of moist air. While experiences in certain areas have dictated some qualifications of the original rule of a 3½ km. depth of moist air for the development of thunderstorm activity, the general usefulness of the concept remains. The second factor discussed by Willett is the cold front aloft which has also been discussed by Holzman [2] and Lichtblau [3].

Namias [4 and 5] has emphasized the usefulness of moist tongues (in isentropic analysis) and their anticyclonic trajectories as related to thunderstorm occurrence. A discussion of this type of phenomenon as referred to constant-pressure or constant-level charts is also included later in this paper. Conversely, the presence or influx of

dry tongues aloft is considered as a deterrent to the development of cumulonimbus clouds [6].

Studies of the movement of individual thunderstorms that have been conducted by the Thunderstorm Project [7] have outdated much previous work and supplied new knowledge on the descriptive phases of the problem at least for the Ohio and Florida areas.

The accepted point of view will be followed in this paper that thunderstorms are the result of the release of atmospheric latent thermal instability and that thunder and lightning which accompany these storms result from processes associated with convection and/or condensation.

The scope of the work undertaken and reported in this paper does not include many interesting phases of the problem such as the dynamics and thermodynamics of convective cells, condensation and precipitation processes, turbulence studies, electrical phenomena, etc. Such phases are fundamental but solutions to most of them are dependent upon detailed observations, analysis and synthesis of data concerning the microstructure of thunderstorms. Therefore this study is restricted largely to synoptic data such as are ordinarily available at weather stations and is directed toward a better understanding of the occurrence and forecasting of thunderstorms as an element of general weather patterns or sequences of patterns. The principal area studied is the Central United States.

Following a detailed examination of the literature, the

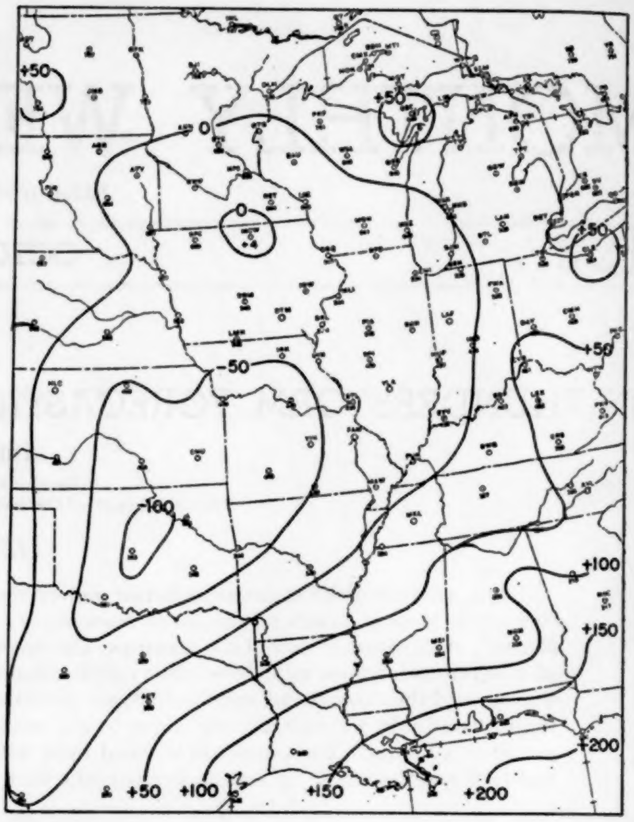


FIGURE 2.—June to July change in total number of thunderstorm days, 1904–43.

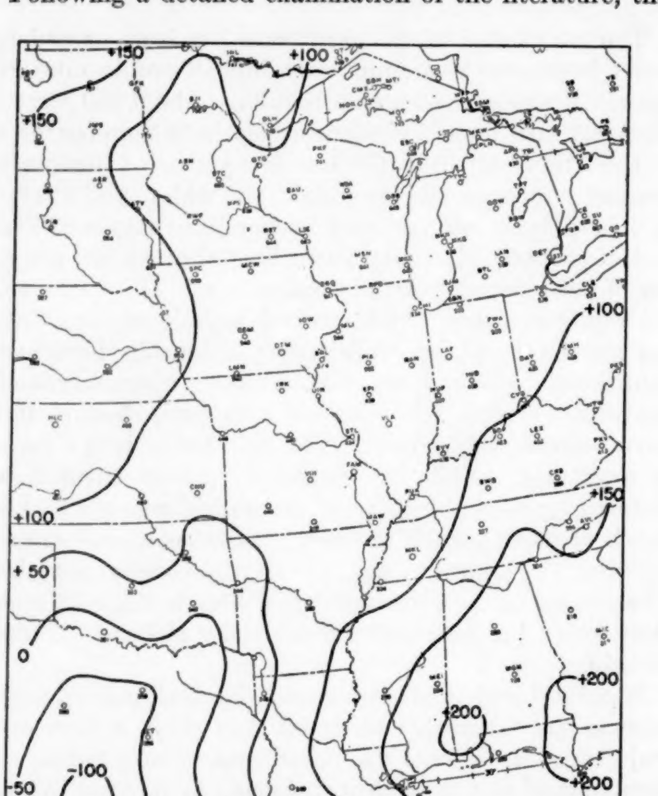


FIGURE 1.—May to June change in total number of thunderstorm days, 1904–43.

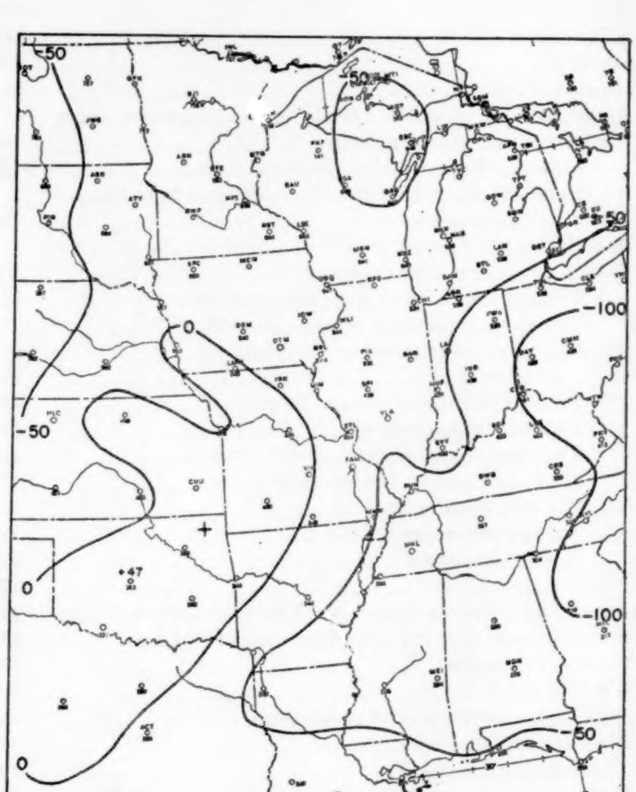


FIGURE 3.—July to August change in total number of thunderstorm days, 1904–43.

general approach of this study was to examine first the climatology of thunderstorms, then case studies of thunderstorm occurrences at individual stations, followed by case studies of areas of thunderstorm activity. This phase was concluded with an attempt to analyze some of the typical features of pre-trough thunderstorm situations. Finally, a preliminary effort was made to incorporate some of the parameters tested in this paper into a technique for forecasting thunderstorms at Chicago.

BROADSCALE PATTERN

ASSOCIATION OF MONTHLY TRENDS OF THUNDERSTORM DAYS WITH WEATHER CHART PATTERNS

Monthly trends of thunderstorm days.—An examination of monthly thunderstorm frequencies for the Central Plains States provides an interesting feature which to many meteorologists is unexpected. A summary of monthly thunderstorm frequencies in the early part of the last decade suggested a sharp decrease in thunderstorm activity at Oklahoma City in July as compared with June and an increase again from July to August. This contrasts with a general tendency toward a July maximum of thunderstorm activity over most of the United States.

Since a 3- to 5-year summary may not be long enough to represent a true mean condition, Alexander's data [8] for a 30-year period were examined. Later more complete data for a 40-year period were obtained from Hydrometeorological Report No. 5 [9]. Data from both sources also showed a July decrease in thunderstorm activity in an area surrounding Oklahoma City.

Complete charts (figs. 1, 2, and 3) were then prepared from Hydrometeorological data depicting monthly changes in the total number of thunderstorm days. These charts show not only the July decrease in thunderstorm activity in the Central Plains region but also an August increase in about the same section while decreases from July to August in other sections tend to prevail.

These variations stimulated inquiry as to the factors that might be related to the monthly variations and thus perhaps also to the occurrence of individual thunderstorms in that area. The importance of the position of the high-level anticyclonic cell as related to rainfall anomalies was developed by Reed [10 and 11] and by Wexler and Namias [12]. Northward movement of the 700-mb. anticyclone from May to June and from June to July is consistent with the decrease in thunderstorm activity in June and July, but this factor does not appear to be consistent with the increase from July to August in the Central Plains region. Correlations by Smith [13] between precipitation and the curvature of surface and 3-km. isobars from 5-day mean charts were statistically highly significant for the Plains States, and the Northeastern States, as well as several other regions not touched upon in this study.

More recently Klein and Winston [14] have related 1947 Iowa summer rainfall to 700-mb. heights and contour curvature on monthly mean charts.

Relation of monthly thunderstorm trends to isobar-isotherm patterns.—For the present study charts which were prepared for the central area between the Appalachians and the Rockies, from several years' upper-air data, depicting the geographical distributions of lapse rate and moisture for various months, gave no positive results. The mean lapse rate at Oklahoma City (1,500 m. to 6,000 m.) was actually slightly greater in July than in either June or August. Mixing ratios remained nearly constant from June to July, but increased in August.

One specific factor that appears to be related to the monthly thunderstorm variation is the cross product of the pressure gradient and the temperature gradient ($\nabla T \times \nabla p$) as determined from mean 2,000-m. charts for the period 1939–44 (figs. 4–7). The cross product of these two terms is approximately proportional to the geostrophic advective term. The convenient term "cross pattern" will be used throughout this paper to designate an area on a chart where the cross product is in the sense of warm geostrophic advection. The 2,000-m. level was used as a compromise. It is probably too low for best representation of the cross pattern over the Western Plains and too high over the Mississippi Valley.

Measurements were made graphically of the degree of cross pattern by comparing a "standard" size cell with the actual size of cells enclosed by crossing pressure and temperature lines when the flow corresponding to the isobar patterns was directed from warm toward cold areas. The "standard" size cell represented a geostrophic advective rate of about 0.8×10^{-5} °C. sec. $^{-1}$ at 40° Lat. After evaluation of the degree of cross pattern on the monthly mean maps, changes from month to month were prepared (figs. 8–10).

Comparisons were then made between these changes of monthly mean cross patterns and changes of the number of thunderstorm days (figs. 11–13) for the same period (1939–44).

A marked increase in the degree of cross pattern from month to month within a given area was usually directly related to a greater increase, or a smaller decrease, in the number of thunderstorm days from the first month to the next as compared with surrounding areas in the Central United States. A marked decrease in the number of cells was consistent with a corresponding decrease in thunderstorm days or a smaller increase than in surrounding areas.

Table 1.—*Comparison of monthly changes in number of thunderstorm days with changes in cross pattern, Oklahoma City, June, July, August, 1945–47*

	Number of thunderstorm days	Change in cross pattern
1945		
June to July	Decrease	Decrease.
July to August	No change	Little change.
1946		
June to July	Decrease	Decrease.
July to August	No change	Slight increase.
1947		
June to July	Decrease	Decrease.
July to August	Decrease	Decrease.

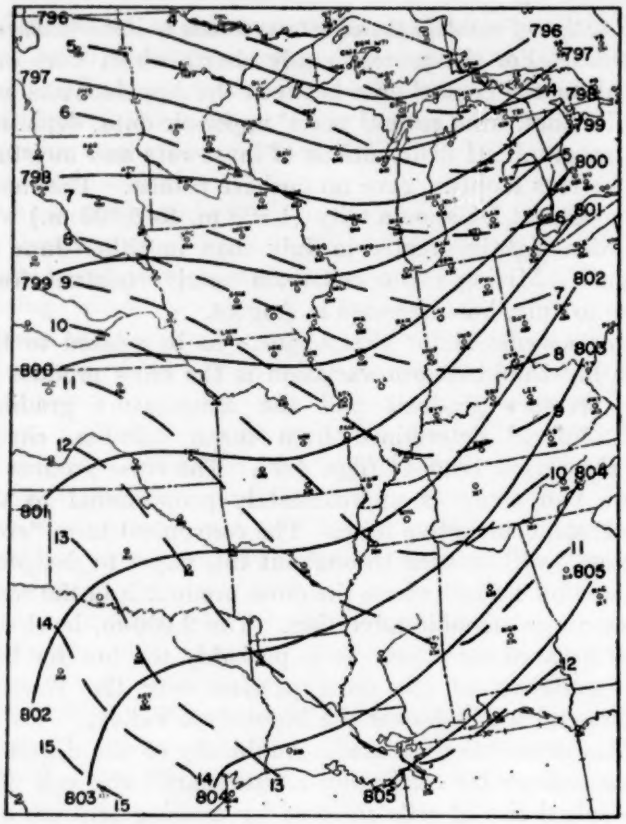


FIGURE 4.—Mean 2000-m. chart for May 1939-44. Dashed lines are isotherms (°C.), solid lines are isobars (mb.).

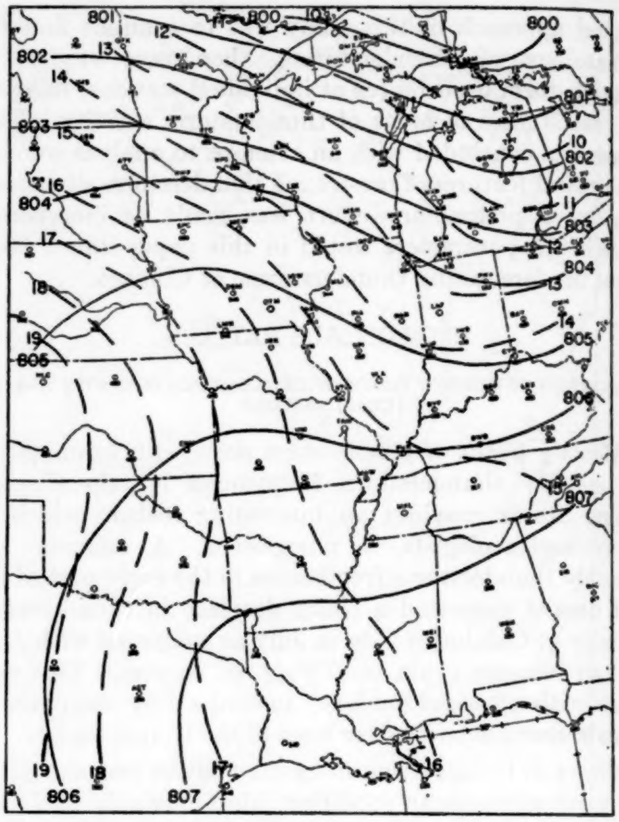


FIGURE 6.—Mean 2000-m. chart for July 1939-44. Dashed lines are isotherms (°C.), solid lines are isobars (mb.).

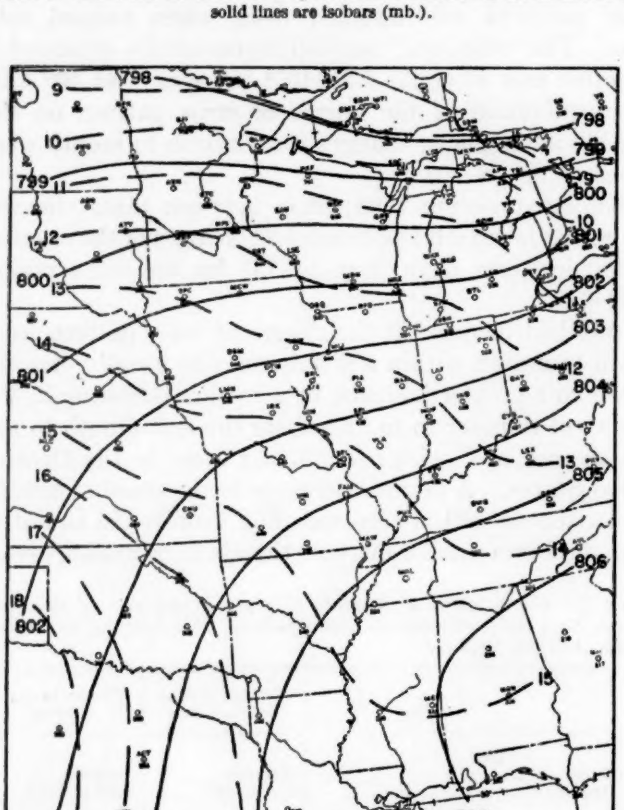


FIGURE 5.—Mean 2000-m. chart for June 1939-44. Dashed lines are isotherms (°C.), solid lines are isobars (mb.).

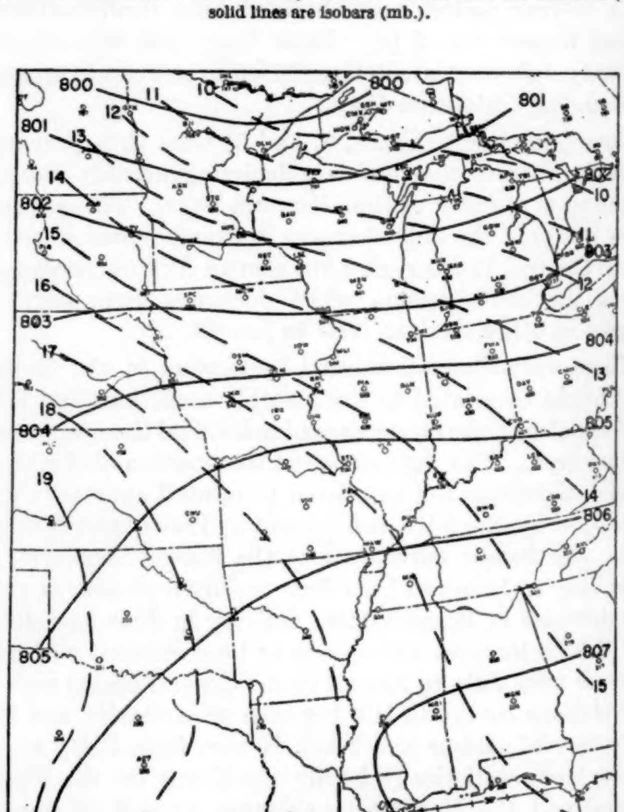


FIGURE 7.—Mean 2000-m. chart for August 1939-44. Dashed lines are isotherms (°C.), solid lines are isobars (mb.).

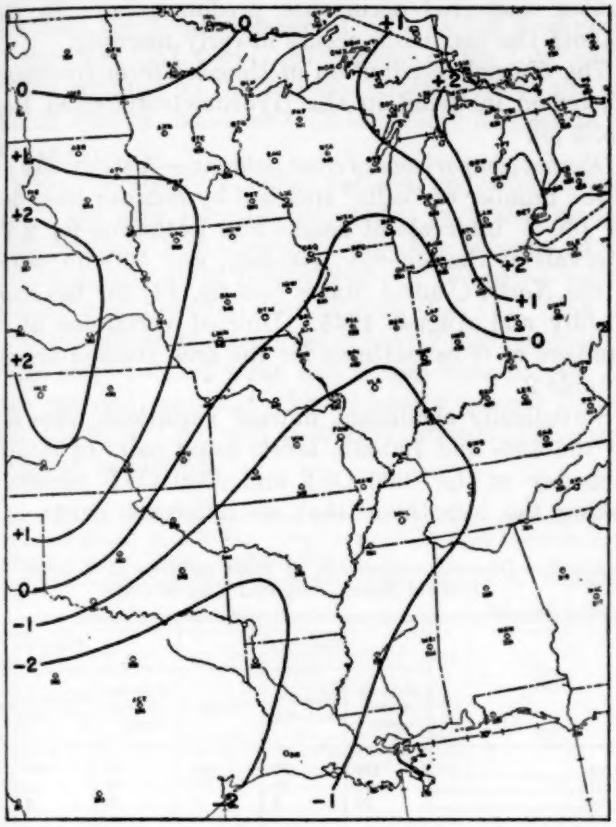


FIGURE 8.—May to June change in mean monthly cross pattern, 2000-m. level, 1939–44. The unit degree of cross pattern is equivalent to a geostrophic advective rate of approximately 0.8×10^{-5} °C. sec.$^{-1}$ at 40° Lat.

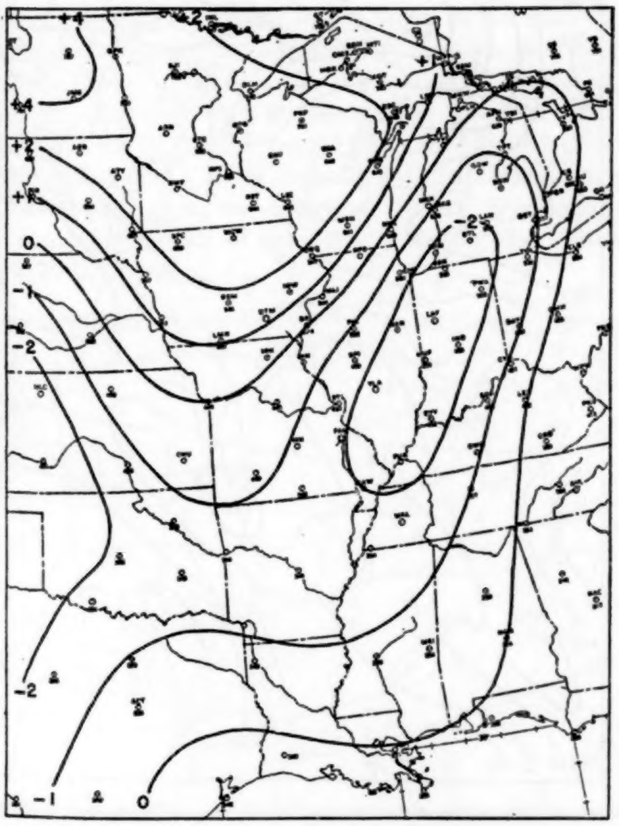


FIGURE 9.—June to July change in mean monthly cross pattern, 2000-m. level, 1939–44. The unit degree of cross pattern is equivalent to a geostrophic advective rate of approximately 0.8×10^{-5} °C. sec.$^{-1}$ at 40° Lat.

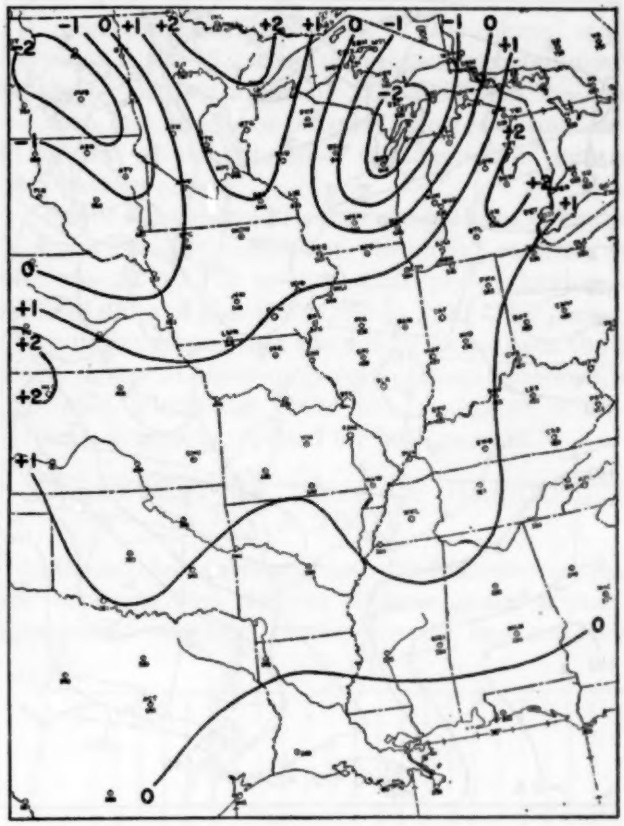


FIGURE 10.—July to August change in mean monthly cross pattern, 2000 m. level, 1939–44. The unit degree of cross pattern is equivalent to a geostrophic advective rate of approximately 0.8×10^{-5} °C. sec.$^{-1}$ at 40° Lat.

A qualitative check of the association of monthly mean 850-mb. cross pattern (from Monthly Weather Review Charts) with the number of thunderstorm days was made using independent data at Oklahoma City for the years 1945 through 1947. These data were especially interesting because the August increase in number of thunderstorm days was not found for these years. The cross-pattern trend was evaluated before the thunderstorm trend was examined. Results are given in table 1.

ASSOCIATION OF DIURNAL TRENDS OF THUNDERSTORM ACTIVITY WITH WEATHER CHART PATTERNS

Diurnal trends of thunderstorm activity.—From the longer-term trends we now turn to shorter diurnal trends in thunderstorm occurrences.

In recent years the 24-hour operation of air transport together with the hourly collection of observational data have called particular attention to the relatively large number of nocturnal thunderstorms occurring in some sections, especially in the Middle West.

The geographical distribution of the hour of maximum occurrence of thunderstorms for July is given by Means [15]. An interesting progression north-northwestward from the Gulf of Mexico occurs starting with the hour of maximum occurrence before noon just inland from the Gulf coast. Farther inland an afternoon maximum is encountered while a little farther, in Oklahoma, Kansas, and Nebraska, as well as areas just to the east of this

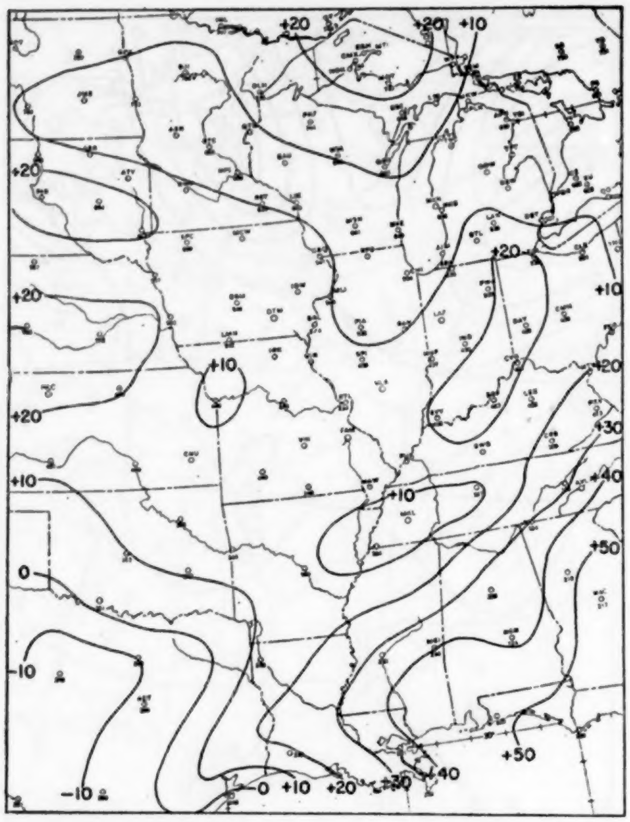


FIGURE 11.—May to June change in the total number of thunderstorm days, 1939–44.

section nocturnal occurrence predominates. In North Dakota the maximum occurs in early morning.

The diurnal distribution of thunderstorm frequency is illustrated in detail in the Hydrometeorological Report No. 5 [9].

Diurnal comparisons of cross patterns.—A study was made of the number of "cells" enclosed by contour lines drawn for 100-ft. intervals of height and isotherms for 2.5° C. intervals at the 850-mb., 700-mb., and 500-mb. surfaces in the North Central States (see fig. 14) for the months of July and August 1945. Diurnal variations of total numbers of cross patterns for the area studied are given in table 2.

Statistically significant diurnal variations were found for the 850- and 700-mb. levels using pairs of totals for each day at the 1000 CST and 2200 CST periods and testing the hypothesis that no difference exists in the

TABLE 2.—*Diurnal comparison of cross patterns at 3 levels, North Central States, July and August 1945*

	1000 CST			2200 CST		
	Cold-to-warm cells	Warm-to cold cells	Totals	Cold-to-warm cells	Warm-to-cold cells	Totals
850 mb	119	167	286	72	148	220
700 mb	91	90	181	67	59	126
500 mb	72	5	77	48	4	52

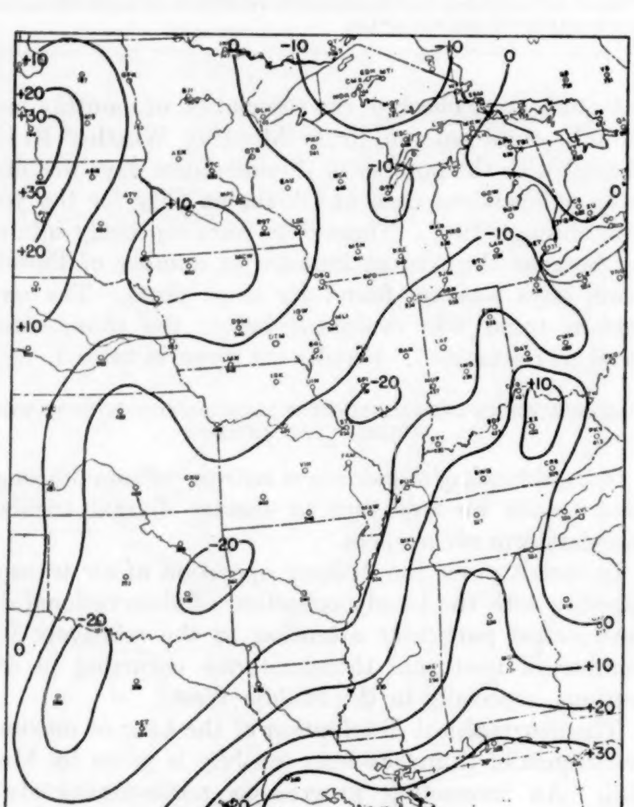


FIGURE 12.—June to July change in the total number of thunderstorm days, 1939–44.

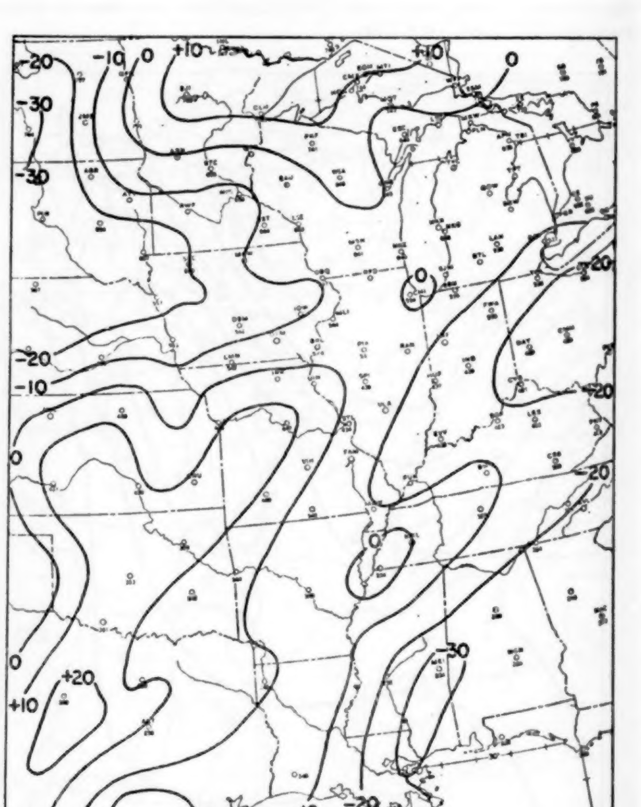


FIGURE 13.—July to August change in the total number of thunderstorm days, 1939–44.

means of the total number of cells at the two periods. At the 2200 CST period, 67 percent of the total number of cells counted on the 850-mb. charts were of the warm to cold variety, while at 1000 CST only 58 percent were of that type.

Areas covered by cross pattern on 850-mb. charts within the area selected for study, were also measured from August 1945 charts. Thus the amount of cross pattern at any given period could be compared with the remainder of the total area studied (fig. 14). The number of thunderstorms reported in hourly teletype sequences in the cross-pattern areas and in non-cross-pattern areas were counted separately for 12-hourly periods following both the 2200 CST and 1000 CST periods. The results are given in table 3.

TABLE 3.—*Diurnal comparison of areas of cross pattern and non-cross pattern at 850 mb. and number of thunderstorm reports, North Central States, August 1945*

	2200 CST	1000 CST
Total units of area covered by cross pattern at 850 mb. (One unit is approximately 10,000 square miles)	934	760
Units of area not covered by cross pattern at 850 mb.	968	1,142
Number of thunderstorm reports during subsequent 12 hours at hourly reporting stations within the portions of the area that were covered by cross pattern on the last 850-mb. chart	675	465
Number of thunderstorm reports during subsequent 12 hours within the portion of the area that was not covered by cross pattern on the last 850-mb. chart	98	126

A larger proportion of the area was covered by cross patterns at the 2200 CST period than at the 1000 CST period. Although less than one-half of the total area was covered by cross pattern, more than 80 percent of the thunderstorm reports were given by stations within cross-pattern areas. Also a larger proportion of thunderstorm reports associated with cross patterns was found for the 2230 CST to 0930 CST period than for the 1030 CST to 2130 CST period. This suggests a diurnal variation with other types such as afternoon local thunderstorms, accounting for more of the activity during the 1030 CST to 2130 CST period.

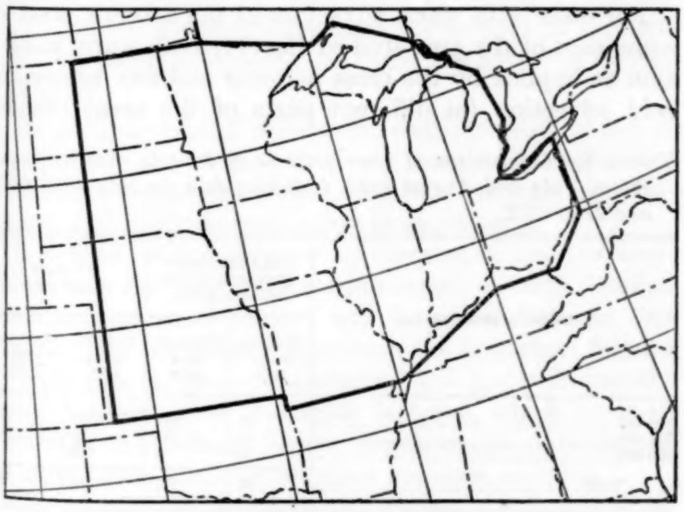


FIGURE 14.—Area of special study is enclosed by heavy line.

A more complete description of this diurnal tendency is given in figure 15. Here the greatest association is found for the period just following 2230 CST and the least for the noon and afternoon periods. However, not less than 70 percent of the afternoon thunderstorms occurred in cross-pattern areas.

Tests of significance of group comparisons of the pooled data gave highly significant "Student" statistic values with the 2230 CST to 0930 CST period having a "t" value of 4.0 and the 1030 CST to 2130 CST period, 3.1. The null hypothesis that the difference between the population means of the two groups of thunderstorms, those associated with, and those not associated with cross patterns, is zero, is rejected for both periods.

DEVELOPMENT OF AREAS OF THUNDERSTORM ACTIVITY

In the careful analyses of many thunderstorm situations new concepts were derived concerning the actual four-dimensional synoptic weather picture and emphases on

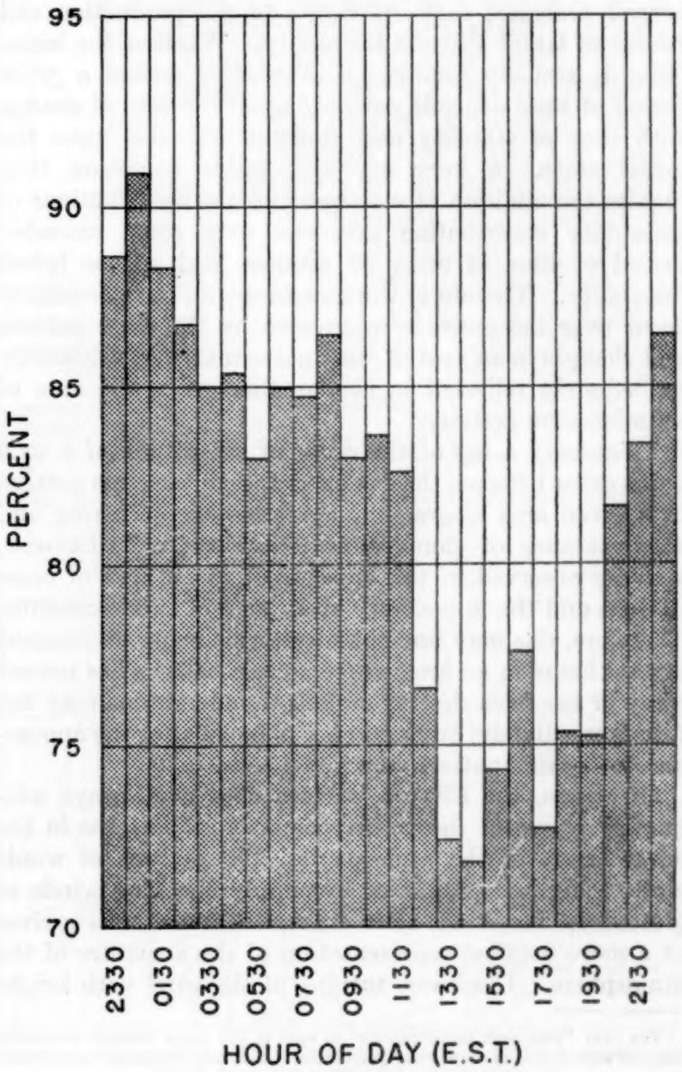


FIGURE 15.—Hourly distribution of running mean (smoothed over 3 consecutive hours) percentage of all thunderstorm activity that was associated with cross patterns on the last 850-mb. chart.

more familiar concepts were shifted. One important shift in emphasis due to the classification and enumeration of individual thunderstorm cases, is the relatively large amount of thunderstorm activity that was found to be of a pre-trough [1] variety as compared with cold-front thunderstorm occurrences. For example, at Chicago during 1943 not a single thunderstorm was classified as having occurred directly with a cold front passage [16]. Certainly a meteorologist will not be surprised that thunderstorms occur ahead of troughs in the central United States, but he may well be impressed with the great proportion of the total activity that is of this type.

In the following paragraphs an attempt is made to give a description of many of the features that appear to be more important in the occurrence of a pre-trough thunderstorm situation in the central United States.

CROSS PATTERNS

The association of thunderstorm activity with cross pattern (or, approximately, the geostrophic advective component) is interpreted as representing not one but several processes that contribute to the production and release of latent thermal instability. Whether the instability is actually produced and released within a given period of time depends not only upon the rate of change with time of stability and moisture but also upon the initial state. A very dry and stable condition may require the addition of moisture and the contributions of instability contributing processes over some extended period of time in order to produce and release latent instability. Therefore, thunderstorms do not necessarily occur over the entire area covered by the cross pattern and changes in an area of cross pattern are not necessarily immediately reflected in similar changes in the area of thunderstorm activity.

Frequently a lag of the order of magnitude of 3 to 9 hours exists between the disappearance of the cross pattern in a given area where thunderstorms are occurring and disappearance of thunderstorm activity; and, likewise, lags are observed in the appearance of an area of cross pattern and the appearance of an area of thunderstorms. Therefore, one may find thunderstorms being maintained several hours in an area where a cross pattern has moved away or has been destroyed; and thunderstorms may not form immediately, but a number of hours after the appearance of a cross pattern in a given area.

Of course, the 850-mb. surface does not always adequately represent the occurrence of cross patterns in the lower layers of the atmosphere. By analysis of winds aloft, using hodographs or by simply checking winds as plotted on the winds-aloft chart, one sometimes arrives at a more detailed representation of the structure of the atmosphere. Clockwise turning of the wind with height is usually consistent with warm-to-cold cross patterns; and counterclockwise turning, with cold-to-warm cross patterns. In regions of higher surface elevation, at North Platte for example, the 850-mb. chart may show no important cross pattern while the winds aloft just above 5,000 feet do reveal important patterns. Also in the Mississippi Valley the 850-mb. chart may show little pattern while minor cross patterns may develop in the winds below the 5,000-foot level and be associated with local development of high stratocumulus, altocumulus, or altostratus-altocumulus-type clouds and possibly showers and thunderstorm activity.

Not only does experience suggest that thunderstorms and cross patterns are related, but several theoretical concepts link the development of atmospheric instability to cross patterns.

Frontal and isentropic convergence.—Frontal and isentropic convergence are, at times, consistent with the occurrence of cross patterns. However, the use of isentropic charts in diagnosing such "upslope" patterns has the disadvantage that, very frequently, an isentropic surface that is selected so that it does not intersect the ground over a large area, may extend so high in other areas that the flow depicted is more in phase with the contours so that the low-level cross patterns are not revealed [5].

One of the contributions intended in this paper is to point out levels at which these cross patterns appear to be more significant for the thunderstorm occurrence.

Differential advection.—Theory also suggests that differential advection may, at times, be related to cross patterns. But if the pattern at only one level is to be related to differential advection, the assumption must be made that less advection of warmer air or some advection of colder air usually occurs at higher levels.

This assumption is supported by tests. Data given in table 2 were stratified according to whether some warm advection was indicated at the 850-mb. level within the area concerned. Results are given in table 4.

For cases with warm advection at the 850-mb. level in some part of the area studied (fig. 14) both warm advection as implied by the cross patterns and any associated cold advection (in different parts of the area) usually

TABLE 4.—*Comparison of cross patterns at 3 levels, North Central States, July and August 1945, including data for both 1000 CST and 2200 CST.*

Constant pressure surface	Cases with warm advection at the 850-mb. level		All cases Total cells	
	Cold-to-warm cells	Warm-to-cold cells	Cold-to-warm cells	Warm-to-cold cells
850 mb	65	315	191	315
700 mb	40	133	158	149
500 mb	25	3	120	9
Total	130	451	469	473

[1] The term "pre-trough thunderstorms" as used in this paper includes occurrences ahead of warm fronts, in warm sectors, and ahead of elongated cold fronts where a warm sector may be well to the north or not well-defined.

decreased with height. Of 77 warm-advection cases in a total of 124 cases, in not more than 5 was there at least one cold-to-warm cell aloft at 700 mb. or 500 mb. directly over warm-to-cold cells at the 850-mb. level. In not more than 6 of the 77 cases was there approximately as much, or more, warm advection indicated at the 700-mb. level as directly below at the 850-mb. level and in no case as much at the 500-mb. level as at the lower levels.

Important exceptions occurred, however. For example, scattered showers and widely scattered thunderstorm activity persisted during the evening of July 5, and on July 6, 1945, in an area of northerly flow at the surface in eastern Minnesota, Wisconsin, Michigan, and northern Illinois where the 2200 CST upper-air charts had indicated increasing cold advection with increasing height to at least 500 mb. Here, both the excess cold advection aloft and warming of the relatively cool air by passage over warmer ground contributed to the maintenance of convection during both night and day.

An interesting balance is found in the totals in table 4. The excess number of warm-to-cold cells at 850 mb. for all cases is nearly balanced by an excess of cold-to-warm cells at 500 mb. Also the number of the two types of cells is nearly equal for the 700-mb. level. Of course, the balance is not known to be required by any a priori reason at these particular levels.

The data suggest that excess heat advected in the lower layers into the area studied may be lost through various processes so that the lower levels become a heat "sink," while at 500 mb. a heat "source" must be present to balance the excess advection of colder air. This heat source and heat sink arrangement in the vertical is consistent with loss of heat from the lower layers to the upper by vertical transport of air in various weather processes and possibly by differences in heat loss through radiation at the two levels. Evaporation with the absorption of latent heat in the lower layers and condensation with the release of latent heat at higher levels are also consistent.

Studies of differential advection on weather charts for two summers brought a recognition of certain characteristic isotherm displacements ahead of troughs at the 850-mb. and 700-mb. levels. Examples are given in figures 16 and 17.

While these typical differential displacements ahead of troughs may not be quantitatively consistent with advection due to modifying factors, they are qualitatively consistent with their corresponding cross patterns.

Low-level, strong, narrow air streams or jets are associated with the pre-trough warm tongue. A more detailed discussion of these factors will be given later in this report. For the present discussion the important feature of such jets is that the center of the jet is frequently found between 2,000 and 8,000 feet msl, which tends to give more localized and greater displacements of isotherms at lower levels until the air mass becomes unstable.

The turning of the wind with height also seems to fit into these comparative displacements and seems to play a part in moving the 850-mb. or 5,000-foot isotherms farther primarily in the area to the west or northwest of the area aloft where the 700-mb. or 10,000-foot isotherms receive their greatest displacement. Subsidence and dynamic warming probably are not entirely unrelated to the warming at the 700-mb. level that is observed over the zone of increasing anticyclonic shear downstream to the east or southeast of the low-level narrow air stream.

Thunderstorm activity seems to be damped under the warm "lid" aloft at 700 mb. in areas where the greatest advance of isotherms at that level has occurred. This is illustrated in the April 1943 case (fig. 17) as well as the August 1945 isotherm movement illustrated in figure 16. A similar pattern of thunderstorm occurrence was found in the April situation.

Turbulence and associated convergence.—Cross patterns are associated not only with upslope convergence and differential advection but also with strong vertical wind

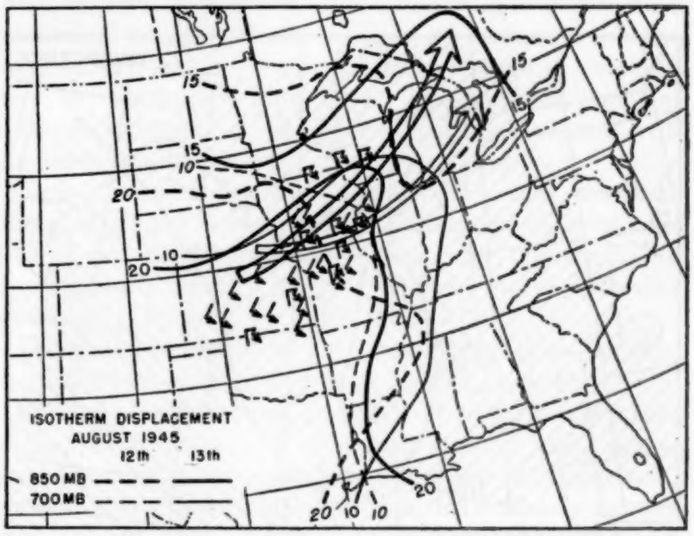


FIGURE 16.—Characteristic isotherm displacement ahead of troughs at 850-mb. and 700-mb. levels, August 12-13, 1945.

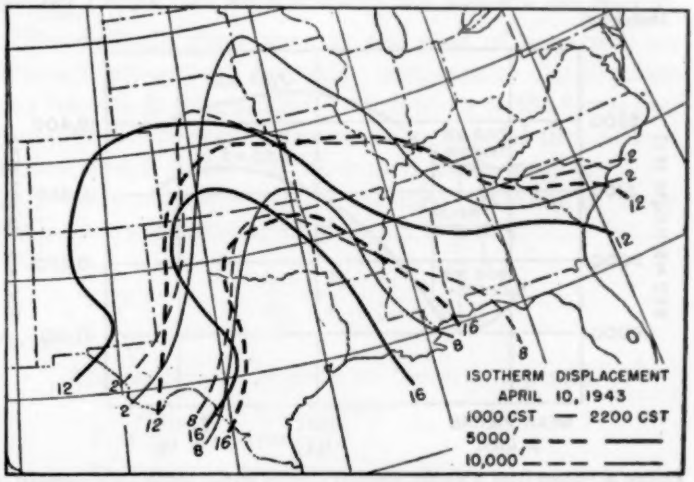


FIGURE 17.—Characteristic isotherm displacement ahead of troughs at 850-mb. and 700-mb. levels, 1000 to 2200 CST, April 10, 1943.

shears. Factors related to the wind shears and to changes in wind shears may be effective in contributing to greater eddy conductivity or vertical transport and mixing of moist air from lower to higher levels and of potentially warmer air from higher to lower levels even though the lapse rate is not quite adiabatic.

Examination of a large number of soundings taken at the time of or just prior to the development of thunderstorm activity usually revealed a lapse rate which is not quite equal to the dry adiabatic in the lower or middle portions of the sounding below the clouds. This was found even when the lapse rate of virtual temperature was plotted.

In spite of less than adiabatic lapse rates, the moisture distributions in such layers frequently suggest rather thorough mixing, with about the same mixing ratio throughout.

Some aspects of this problem were considered by Mollwo [17]. He studied the problem of estimating the wind component normal to the isobars due to eddy viscosity

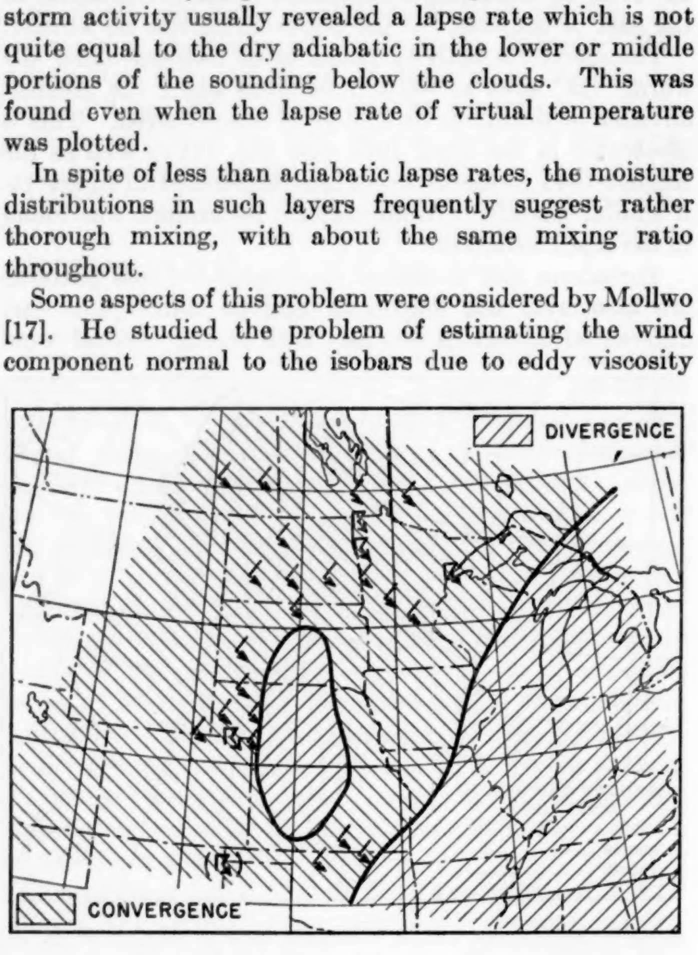


FIGURE 18.—Thunderstorms as associated with areas of convergence and divergence computed from cross-isobar wind components at 2200 CST, August 7, 1944.—*See Mollwo* [17].

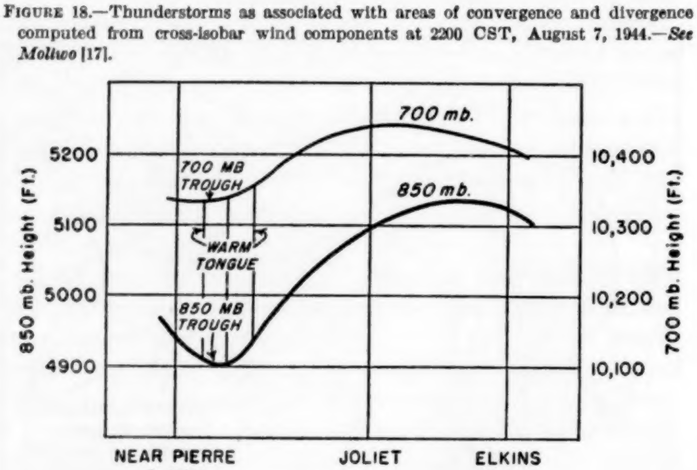


FIGURE 19.—Steep slope of 850-mb. constant pressure surface immediately southeast of warm tongue, 2200 CST, August 4, 1945.

and wind shear above the gradient-wind level. Taking a simple case, he assumed that the vertical variation of the gradient wind is due to horizontal temperature gradients. His derived equation relates rate of change of wind shear with height (which is proportional to the cross-isobar wind component) to change of temperature gradient with height.

From certain mean data, Mollwo arrived at computed cross-isobar wind velocities of the order of magnitude of 1 to 2 cm. sec.$^{-1}$ and pointed out their importance in large scale horizontal divergence and convergence. From individual midwestern situations (for example, Oklahoma City to Dodge City on August 28, 1945, 2200 CST data) the author has computed much larger values—of the order of magnitude of 50 cm. sec.$^{-1}$.

These values were computed using the same value of the coefficient of eddy transfer that was used by Mollwo, 100 gm. cm. $^{-1}$ sec.$^{-1}$. The value of this coefficient may, of course, be less or actually may become much larger in certain situations with especially steep lapse rates and strong wind shears similar to those experienced in pre-trough thunderstorm situations.

Cross-isobar wind components of this order of magnitude may provide important contributions, through horizontal divergence or convergence, not only to pressure variations but also to convergent depth of moist currents. This important phenomenon could be especially important in southerly jets just east of the Rockies where large changes in temperature gradients with height are found. A similar but more general relationship was derived by Starr [18].

Charts were prepared from data for August 1944, which provided a basis for graphical estimation of this type of convergence over the central United States. Temperature data for the 5,000- and 20,000-foot levels were used. Then an attempt was made to relate those map patterns to the occurrence of thunderstorm activity. An example of the patterns of convergence and divergence as computed is given for August 7, 1944, 2200 CST, together with thunderstorm and lightning reports as taken from the hourly sequences (fig. 18). Areas of thunderstorm activity usually were found within the areas of implied convergence.

The data are consistent with the concept of cross-isobar flow and convergence or divergence, being related to the computed rate of change of temperature gradient or wind shear with height.

Since cross patterns at the 5,000-foot or 850-mb. level are usually related to wind shears that seldom are uniform with height, some relationship between areas of cross patterns and zones of turbulence convergence might be expected, and, in fact, is found.

Billow-type clouds might be expected in zones of strong and variable wind shear where eddy transfer is contributing to considerable transport of moisture from lower to higher levels. Altostratus-altocumulus cloud decks are the most frequent cloud predecessors of pre-trough thunderstorm

activity. Bases of such cloud decks are usually extremely well-defined as the typical Midwest thunderstorm situation develops, suggesting considerable vertical motion of a general or widespread type, since the cloud decks are usually overcast and not scattered to broken as with simple convection cells.

Cross patterns, therefore, must be consistent with and indicative of the occurrence of this type of convergence as well as upslope convergence and differential advection.

Cross patterns and pressure changes.—Interesting correlations have been observed between 12-hour pressure changes at sea level and the occurrence of cross patterns. The two factors are interrelated. An isallobaric wave aloft moving into the Central United States from the west or northwest may contribute to the development of an out-of-phase isobar-isotherm relationship in the lower layers as the wave reacts with the persistent summer configurations of the temperature field. Valuable information for forecasting the movement of cross patterns can frequently be gained by making use of movements of 12-hour isallobaric patterns for extrapolating wave displacements. On the other hand, minor 12-hour pressure falls at sea level have been observed to remain closely associated with cross patterns on the 850-mb. charts. Minor trough developments and frontogenesis such as occur with localized pre-trough pressure falls frequently may be associated with locally pronounced cross patterns at the 850-mb. level.

VELOCITY DISTRIBUTION

Narrow air streams (jets).—Frequently the greatest values of $\nabla T \times \nabla p$ on the 850-mb. chart are found in the vicinity of the narrow southerly or southwesterly air streams (or jets) that are prone to appear at lower levels in advance of pressure troughs. The occurrence of such strong narrow currents at relatively low levels is consistent (fig. 19) with the hydrostatic implications of the warm tongue in the mean isotherms ahead of troughs, with winds tending to increase downward on the southeastern side of an elongated warm tongue (then warmer air is found toward lower pressure), and tending to decrease downward on the northwestern side of the warm tongue (where cooler air is found toward lower pressure).

Even though strong southwesterly winds are to be expected with strong pressure gradients that are found preceding such troughs, wind speeds frequently appear to be greater than the expected geostrophic or gradient speeds. A significant "t" test value supported the conclusion that super-geostrophic winds are found in southerly jets where isotherms are approximately parallel to the streamlines with warmer air toward lower pressure.

Horizontal shears.—Strong narrow air streams (or jets) must be associated by definition with important horizontal shears, with anticyclonic shears on the east of the southerly current and with cyclonic shears on the west.

Especially strong anticyclonic shears are observed on the east side of some of the more important narrow air streams observed in the vicinity of the 5,000-foot level in the Middle West. At many times, these shears approach the value of minus the Coriolis parameter for middle latitudes. Occasionally the shears may exceed in value the criterion for lateral instability [19]. Some examples, together with their corresponding shear values, are as follows:

Aug. 8, 1944	1600 GMT	St. Paul to La Crosse—slightly less than minus $.9 \times 10^{-4}$.
Aug. 10, 1944	0400 GMT	St. Paul to La Crosse—slightly less than minus $.8 \times 10^{-4}$.
Aug. 10, 1944	1600 GMT	Milwaukee to Joliet—approximately minus 1.0×10^{-4}.
July 16, 1945	0400 GMT	Sioux City to Des Moines—less than minus $.7 \times 10^{-4}$.

Since shear is one of the components of vorticity, important applications of the vorticity theorem may be made to these narrow streams and their corresponding shear patterns. For example, if trajectories of adjacent southerly air currents encounter increasing anticyclonic shear in certain portions of a narrow stream structure (assuming no important changes in curvature of the trajectories) that is greater than the change in vorticity due to northward latitudinal displacement, general divergence instead of convergence will be associated with the southerly flow.

Such divergence is revealed in the persistent stratification of moisture as measured in radiosonde observations. This type of development damps the occurrence of thunderstorm activity in spite of many other favorable factors.

Dates of occurrence of this type of situation include: August 15, 25, and 26, September 3 and 16, 1945.

Similarly, with intense gradients of mean temperature to the west or northwest of narrow streams aloft, strong northerly flow in the lower layers may occur. Increasing cyclonic shears along trajectories in the northerly current may be sufficient to overcompensate the change in vorticity due to southward latitudinal displacement giving general convergence instead of divergence in the northerly current.

The cyclonic shear zone in the west of a narrow air stream together with favorable temperature distributions may become frontogenetical contributing to the formation of new fronts or shear lines in the vicinity of the induced surface trough under the pre-trough warm tongue.

Upon examination of the vorticity theorem in more detail a very interesting application is found.

$$\frac{\Delta p_2}{\Delta p_1} = \frac{f_2 + \zeta_2}{f_1 + \zeta_1}$$

where

Δp = increment of pressure between top and bottom of air column.

f = Coriolis parameter

ζ = vorticity relative to the earth.

When the initial absolute vorticity is very low, say in an

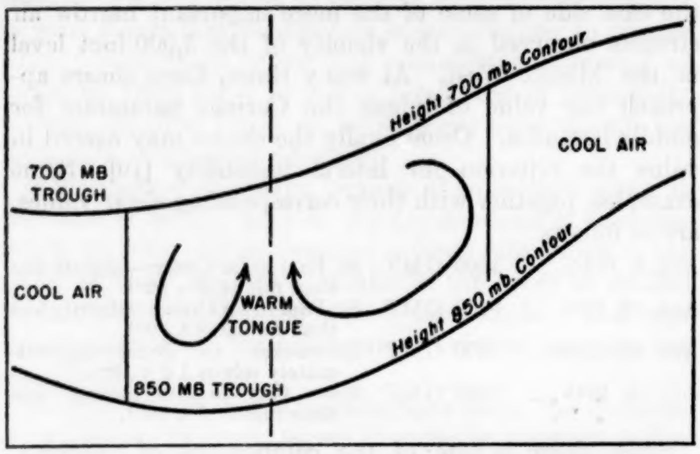


FIGURE 20.—Solenoidal fields associated with circulation accelerations suggesting low level convergence.

anticyclonic shear situation with straight flow, a small increase either in latitude or in vorticity relative to the earth is consistent with a relatively large stretching of the air column as compared with a situation in which cyclonic shear was originally present and the same change in vorticity occurred.

This may help to explain some of the rapidly developing and rapidly changing weather situations that plague forecasters in the Middle West especially in summer when anticyclonic shear patterns are frequent in the Southern Plains.

WARM TONGUES

Previously in this paper (fig. 19) warm tongues and southerly jets were shown to be interrelated. The hydrostatic analysis suggests strong pressure gradients and strong winds in the lower levels on the eastern or southeastern side of the mean warm tongue. The warm tongue, on the other hand, may be further elongated in certain slow-moving patterns by advective action in the narrow air stream. Here, then, is one of the unstable situations having some of the aspects of a "chain reaction," that seems peculiar to the warm tongue.

Solenoidal fields that appear in a cross section through a warm tongue are associated with circulation accelerations that suggest convergence in the lower levels (fig. 20). Lapse rates also are usually relatively steep above a low-level warm tongue since the warm tongue is seldom so elongated at higher elevations. These factors, together with large amounts of moisture, which as in isentropic analysis are usually found associated with warm tongues, and the effective contribution of any cross patterns found within the warm tongue, provide a very favorable system for the development and release of instability.

After the development of thunderstorm activity in the vicinity, the unstable situation tends to persist due to the fact that warm advection and the release of latent heat tend to maintain solenoidal fields in spite of general cooling contributed by convergence. Thunderstorm activity, therefore, tends to persist in warm tongues even after any cross patterns within them have become relatively weak.

Attention has also been directed to the importance of warm tongue phenomena by the occurrence of severe thunderstorm activity and sometimes tornadoes in the vicinity of the more narrow elongated warm tongues.

Severe thunderstorms that were associated with a narrow warm tongue aloft in the Lehigh Valley area the night of July 9–10, 1945, contributed to the loss of several lives in flash floods. On July 24, strong winds with a thunderstorm squall line associated with a narrow warm tongue aloft struck Glenview, Ill., northwest of Chicago. The thunderstorm at Washington, D. C., on June 2, 1945, which was accompanied by considerable hail, was also associated with a warm tongue aloft.

Prefrontal squall lines [2] have been associated with cold fronts aloft in the literature. The observed relationship between warm tongues aloft and prefrontal squall lines implies a relationship between cold fronts aloft and warm tongues.

A small amount of careful study reveals that synoptic characteristics on the sea level chart under warm tongues aloft are quite similar to those under cold fronts aloft. Surface winds are likely to give little indication of either a warm tongue or cold front aloft except just prior to or with the development of a burst of thunderstorm activity. Surface three-hourly pressure changes will reflect both a moving warm tongue and a moving cold front aloft with a falling then rising characteristic or falling then falling less rapidly. Presumably a cold front aloft should give a sharper kink in the barogram than a warm tongue without a front, but if thunderstorms are occurring in the vicinity with resulting irregular barograms, such a distinction may be difficult or impossible to make. A more or less linear arrangement of slight discontinuities could result from either situation. A poorly defined surface trough might be expected ahead of the surface cold front in either case.

Of course, the presence of an extensive deck of middle type clouds with altocumulus characteristics and an elongated area of thunderstorms well ahead of a front need not be a specific indication of a cold front aloft.

The occurrence of warm tongues together with the occurrence of cold fronts aloft is very likely, but cold fronts aloft are expected to be accompanied by an upper-air wind shift. Warm tongues are more likely to be associated with such wind shifts at lower rather than at higher levels.

Continuity is a major tool in frontal analysis. But continuity of weather patterns associated with warm tongues also is observed. When the direction of the winds at the 5,000-foot level makes a large angle with the direction of the elongation of the warm tongue, the warm tongue together with its associated area of thunderstorm

[2] The term "instability line" has come into recent use by international agreement to represent nonfrontal squall lines [21].

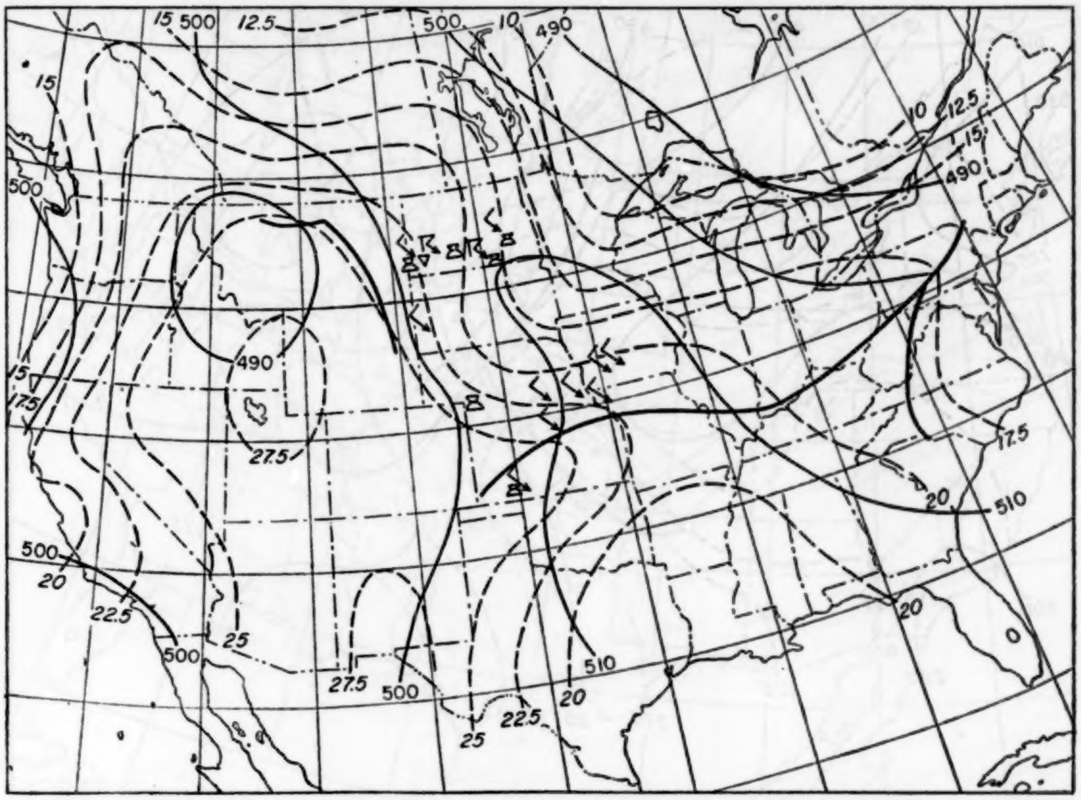


FIGURE 21.—850-mb. chart, 2200 CST, August 2, 1945. Solid lines are height contours labeled in tens of feet. Dashed lines are isotherms (°C.). Heavy solid lines indicate the 0030 CST positions of the sea level fronts taken from the Daily Weather Map (Washington, D. C.). Thunderstorm data are from the 0030 CST reports.

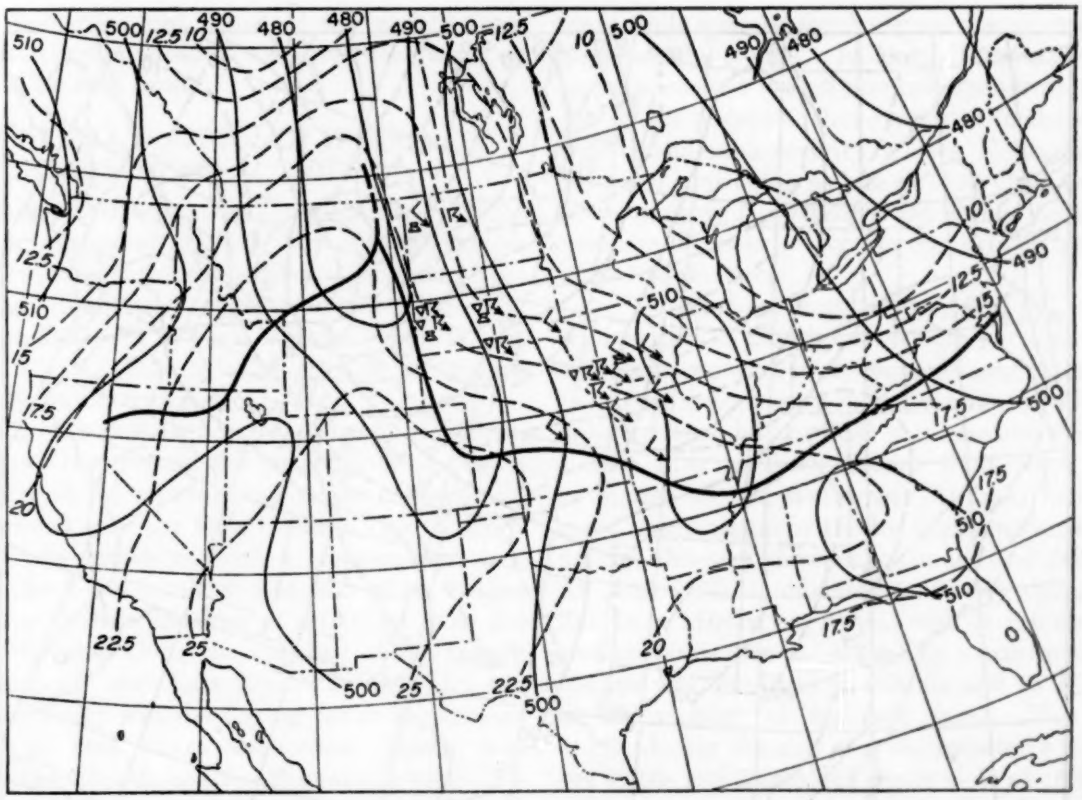


FIGURE 22.—850-mb. chart, 2200 CST, August 3, 1945. Solid lines are height contours labeled in tens of feet. Dashed lines are isotherms (°C.). Heavy solid lines indicate the 0030 CST positions of the sea level fronts taken from the Daily Weather Map (Washington, D. C.). Thunderstorm data are from the 0030 CST reports.

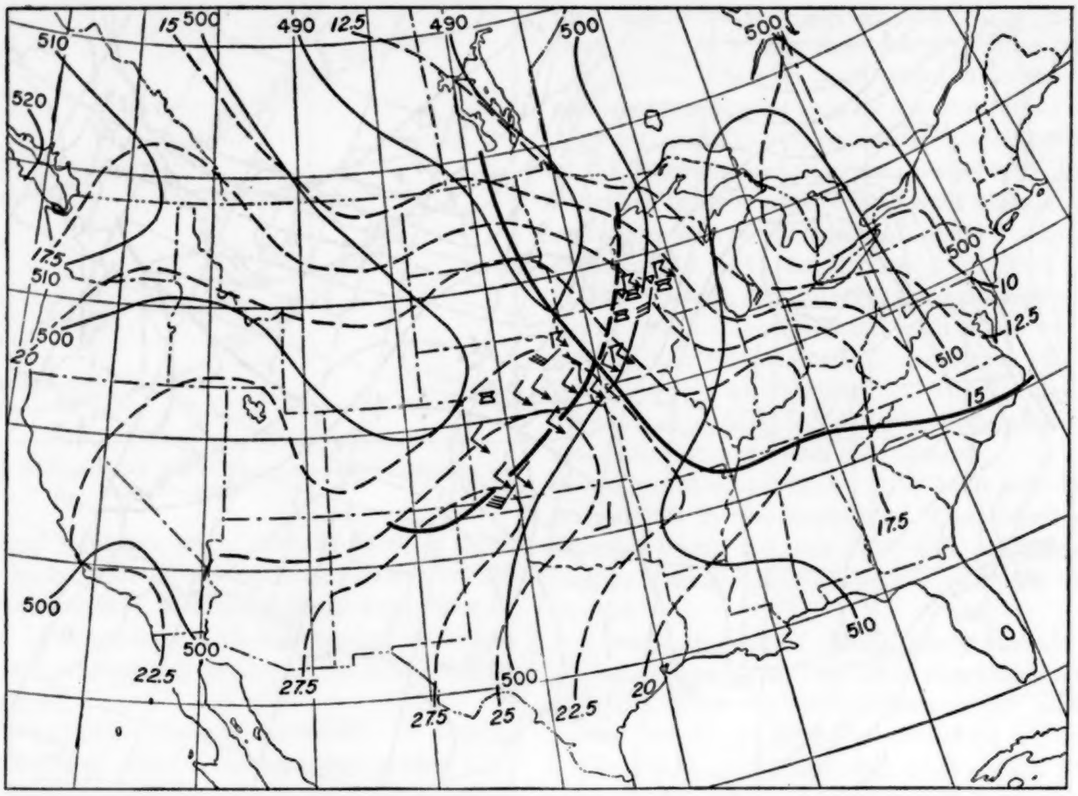


FIGURE 23.—850-mb. chart, 2200 CST, August 4, 1945. Solid lines are height contours labeled in tens of feet. Dashed lines are isotherms (°C.). Heavy solid lines indicate the 0030 CST positions of the sea level fronts taken from the Daily Weather Map (Washington, D. C.). Thunderstorm data are from the 0030 CST reports.

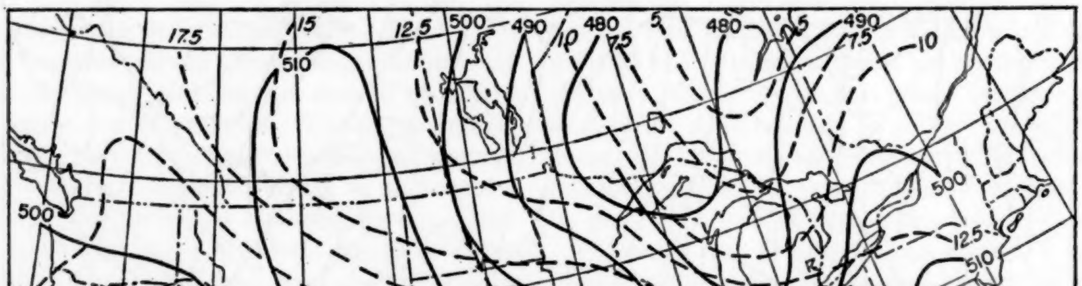


FIGURE 24.—850-mb. chart, 2200 CST, August 5, 1945. Solid lines are height contours labeled in tens of feet. Dashed lines are isotherms (°C.). Heavy solid lines indicate the 0030 CST positions of the sea level fronts taken from the Daily Weather Map (Washington, D. C.). Thunderstorm data are from the 0030 CST reports.

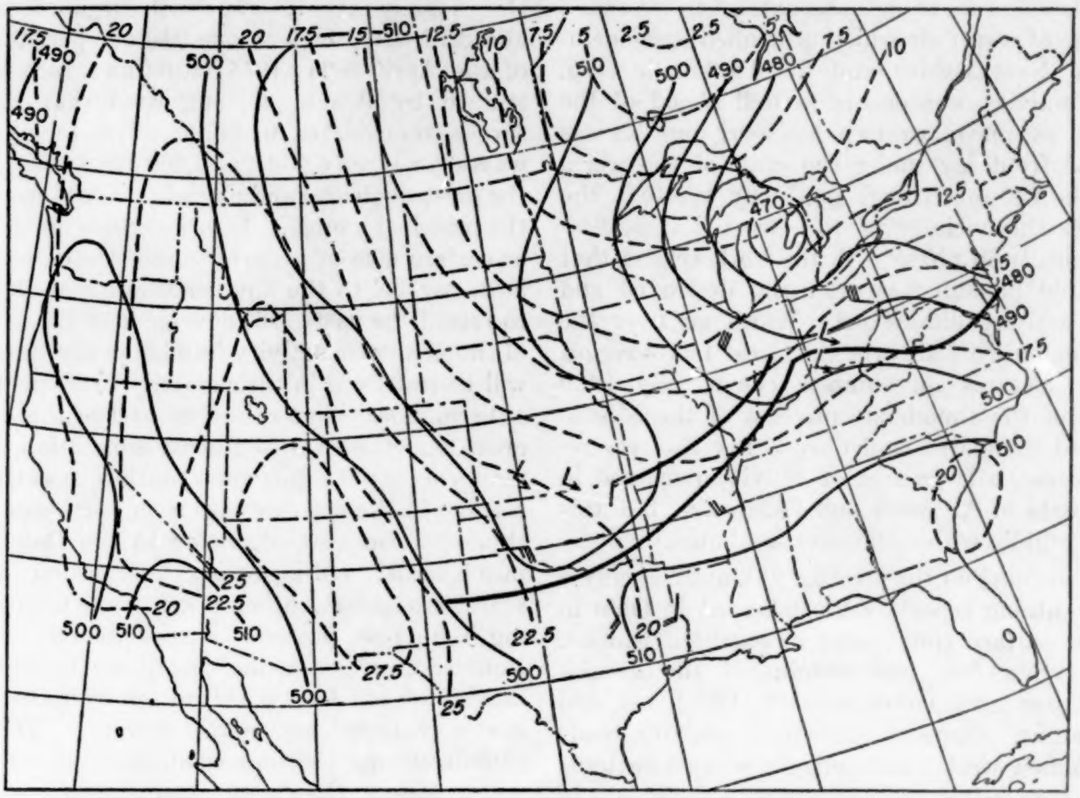


FIGURE 25.—850-mb. chart, 2200 CST, August 6, 1945. Solid lines are height contours labeled in tens of feet. Dashed lines are isotherms (°C.). Heavy solid lines indicate the 0030 CST positions of the sea level fronts taken from the Daily Weather Map (Washington, D. C.). Thunderstorm data are from the 0030 CST reports.

activity may be carried out ahead of the surface front with approximately the speed of the 5,000-foot wind, as would an upper-air cold front.

MOVEMENT AND LIFE CYCLE OF PRE-TROUGH THUNDERSTORM ACTIVITY

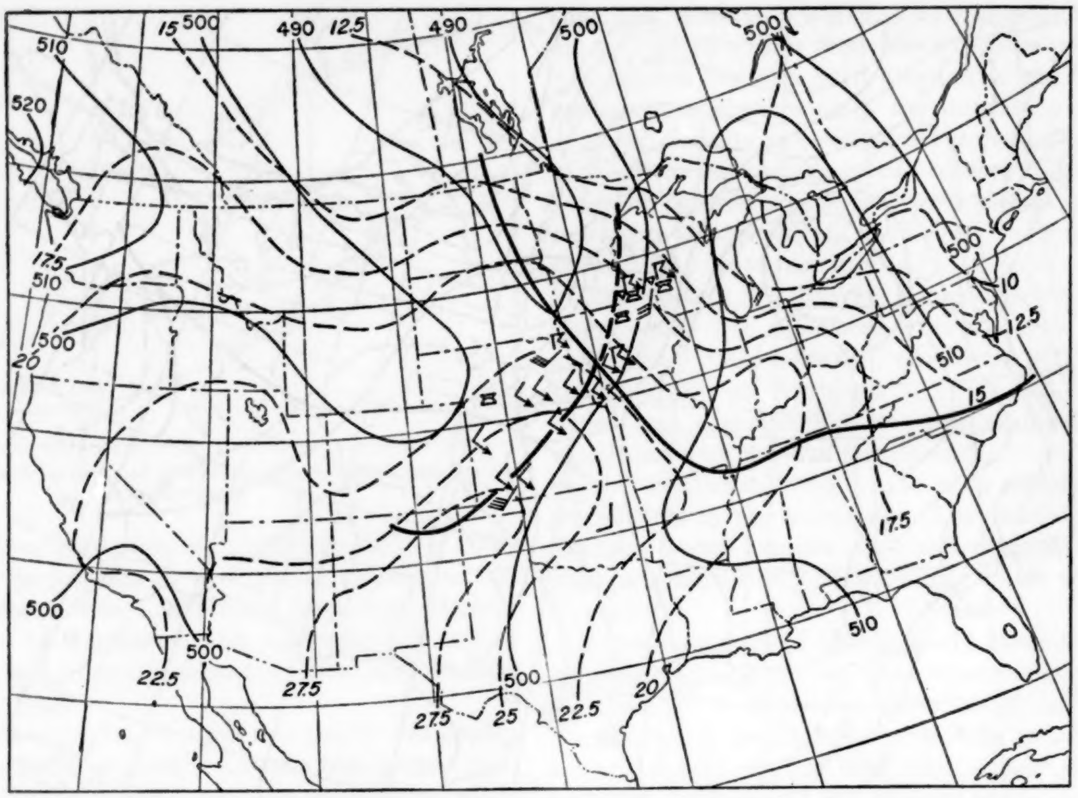
Having discussed, briefly, individual features of the pre-trough structure and of the formation of thunderstorm activity, we now are confronted with the problem of the movement and dissipation of thunderstorm activity. Referring to the 2200 CST 850-mb. chart sequence for the period August 2 to 6, 1945, inclusive (figs. 21 to 25), we see such a cycle demonstrated.

On the 2d (fig. 21) thunderstorm activity in Nebraska, Kansas, and Iowa represented the latter phase of a cycle which occurred with the eastward movement of the previous trough observed near the East Coast. This thunderstorm activity was associated with a cross-pattern area that persisted along the northern side of a warm tongue extending eastward from the hub of warm air over the western Plateau region along the remnant of the trough that connected with the East Coast trough. In the Dakotas some activity was developing far in advance of the trough in an area where some cross pattern was represented on the 850-mb. chart. Bismarck's 1000 CST radiosonde observation indicated a layer of moist air about 3 km. deep.

On the 3d (fig. 22), the trough and ridges moved eastward while a strong southerly narrow air stream developed ahead of the trough. In North Dakota, where the cross pattern was not so well-marked, thunderstorms dissipated during the night but thunderstorms to the south persisted with considerable activity in Iowa, Nebraska, Kansas, and Missouri continuing as late as 0730 CST, as the center of activity moved southeastward along the isotherms into northern Missouri. By afternoon little activity was reported in this area.

On the next evening, the 4th (fig. 23), thunderstorms redeveloped in the region of cross pattern. At this time surface fronts were in the same general vicinity. By 0730 the thunderstorm area in the vicinity of the more intense cross pattern had shifted southeastward along the isotherms into northern Illinois with very little activity remaining to the southwest. Diurnal factors again became predominant with the thunderstorms mostly dissipating, although showers continued and drifted eastward. At 1530 CST thunderstorm activity developed along a line from Muskegon, Mich., well to the northeast of the surface warm front, extending southwestward to near Moline and Bradford in Illinois and to Kirksville, Mo., in the vicinity of the cold front. This development occurred near the axis of a southwesterly jet as shown by the 4,000- and 5,000-foot winds aloft at 1600 CST.

The most active phase of the thunderstorm cycle was then developing. By evening on the 5th (fig. 24), widespread thunderstorm activity was occurring on the for-



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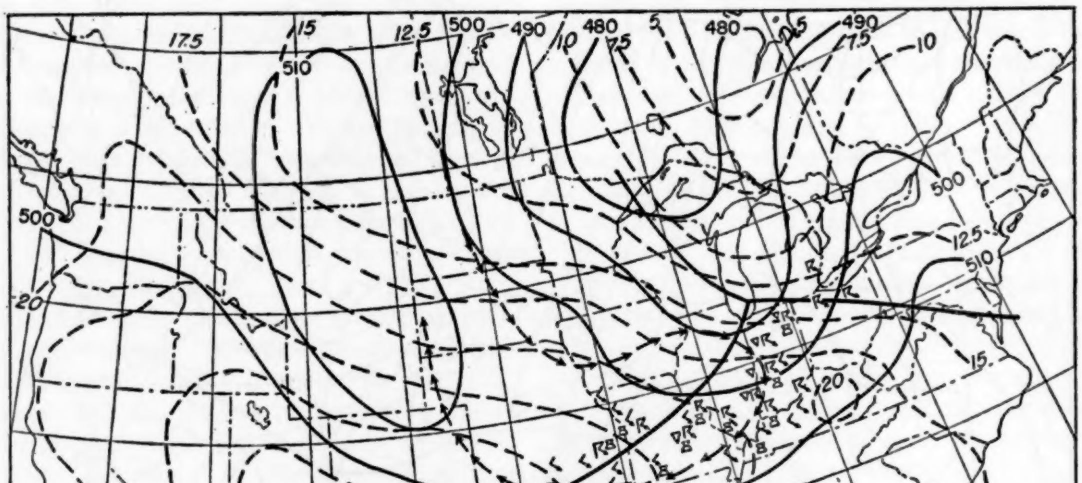

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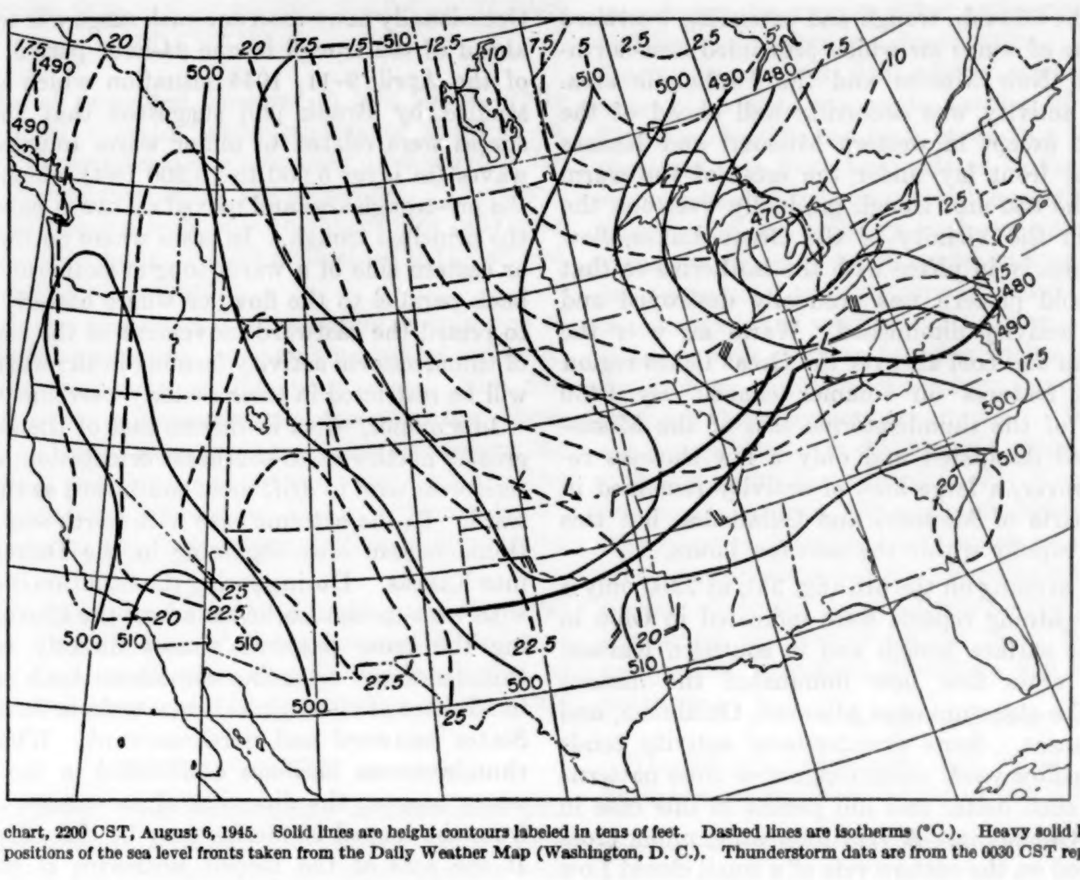

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ward side of the 850-mb. trough and extending westward into the tongue of warm air which protruded east-northeastward from New Mexico and the Panhandle area. Most of this activity was occurring well ahead of the surface trough except in western Missouri and Kansas where the cold front lay under the crest of the warm tongue. As the 850-mb. trough gradually overtook the cold tongue in the vicinity of the Great Lakes, flow became more nearly in phase with the isotherms so that the warm-to-cold pattern was gradually destroyed and thunderstorm activity diminished. Warm air over the western Plateau and cool air over the Great Lakes region are persistent features on summer charts. By 0430 practically all of the thunderstorms east of the Mississippi River had dissipated and only a few showers remained. However, a large area of activity remained in Kansas and parts of Missouri and Oklahoma, but this too dissipated rapidly within the next few hours.

By the next evening on the 6th (fig. 25), at 2200 only a few isolated lightning reports were indicated in Ohio in advance of the surface trough and in southern Kansas. Cold-to-warm cross flow now dominated the district with a delta-like structure over Missouri, Oklahoma, and northern Arkansas. Some thunderstorm activity tends to persist in shallow weak warm tongues or cross patterns just ahead of such deltas and did persist in this case in Arkansas and Oklahoma. A very interesting minor cross pattern occurred on the eastern side of a small closed Low that was suggested by the winds aloft in Lower Michigan. Showers and at least one thunderstorm occurred a few hours later in this region.

On the evening of the 7th small amounts of thunderstorm activity persisted in eastern Colorado with a few showers in western Nebraska.

By the evening of the 8th, thunderstorms were appearing in the western Dakotas again in advance of another trough.

The principal area of thunderstorm activity described very nearly a closed path in an anticyclonic sense (fig. 24), similar to the case described by Namias [4]. In the present example the movement of the area of maximum thunderstorm activity was consistent with the trajectory of the area of cross pattern as the warm tongue ahead of the trough rotated clockwise around the "hub" of warm air over the southwestern mountain and plateau area. The trajectory of the individual warm moist air parcels was, of course, somewhat different from that of the complete cycle of thunderstorm activity.

Individual surges of thunderstorm activity, once they were established in the evening over a general area, showed a tendency to drift eastward or southeastward along the 850-mb. isotherms tending to outpace the movement of the major trough pattern with which they were associated. With slow-moving troughs the surges tend to develop the next evening near or even to the rear of the position where the thunderstorm activity dissipated during the morning. Occasionally more than one such surge will travel eastward ahead of the trough in one 24-hour period. An analysis of the April 9–11, 1944 situation which was originally studied by Brunk [20] suggested that such successive surges were related to minor warm tongues or isotherm waves (in layer 5,000 to 10,000 feet) which developed in the pre-trough area and moved eastward more rapidly than the principal trough. In cases where on the southeastern or eastern side of a warm tongue isotherms bend sharply back parallel to the flow, or where easterly flow is likely to retard the eastward movement of the isotherms, areas of thunderstorm activity forming in the warm tongue area will be restricted in their easterly movement.

In summer, when isotherms east of the Rockies have a greater northwest-to-southeast orientation, areas of thunderstorms tend to drift more southward as they move eastward. In the extreme case with north-south isotherms a thunderstorm area beginning in the Dakotas may drift into Kansas. During spring the situation is quite different with west-to-east isotherms across the United States steering the cross patterns almost directly eastward with thunderstorms occurring sometimes both night and day in advance of a trough as it moves from the South Central States eastward and northeastward. When an area of thunderstorms becomes established in the vicinity of a warm tongue, the direction of movement as determined from the looped isotherms may be difficult to determine. If the axis of the looped isotherms is parallel to the flow (5,000 to 10,000 feet) the area of activity may be extended to some degree along the axis of flow. If the warm tongue is approximately normal to the flow, the thunderstorm area will move with the approximate velocity of the flow, not infrequently taking on the characteristics of a squall zone as it progresses.

During the late spring and early summer the "hub" of warm air over the western mountain and plateau States is not as well established and may be carried eastward in a fairly strong circulation during the night and early morning. Cross patterns and thunderstorms will also drift eastward ahead of the warm air. Intense insolation during the day will tend to reestablish the center of the warm air over the Southwest so that cross patterns occur farther west and areas of thunderstorm activity are reestablished farther west to again drift eastward.

The movement of individual thunderstorms must, of course, be distinguished from the movement of areas of thunderstorm activity. Individual thunderstorms, according to individual station reports, frequently have a movement somewhat different from that of the area of thunderstorm activity. The Thunderstorm Project reports [7] that the direction of movement of individual cells in Florida and Ohio corresponds well to that of the mean wind vector, gradient level to 20,000 feet. Movement of areas of thunderstorms is mainly along the 850-mb. isotherms with a slight component of motion across the isotherms toward colder air. This direction of movement frequently is similar to that of the 20,000-foot flow.

A TECHNIQUE FOR FORECASTING THUNDERSTORMS AT CHICAGO

The material presented thus far in this paper, while directed toward a better understanding of the way in which thunderstorms occur, is primarily qualitative so far as applications to forecasting are concerned. Therefore, it was desirable that a technique be outlined for providing the forecaster with a quantitative estimate of the likelihood of thunderstorms at Chicago.

The technique presented in this section is only one of many possible approaches, each making use of different, but actually somewhat similar, parameters. The discussion in previous sections of parameters other than those used in the technique may prove useful for forecasting the timing or areal distribution about the point for which the technique is specifically prepared, also as a "source book" of parameters for the further preparation of forecasting techniques.

A test was made of a forecast aid making use of several of the more simple factors that are frequently used separately and in a qualitative way for the prediction of thunderstorm occurrence at Chicago within a given 24-hour period.

SELECTION OF FACTORS

Charts depicting flow, temperature, and moisture patterns at the 850-mb. level are the primary tool. Temperatures from the 500-mb. level are used together with 850-mb. temperatures for a rough estimate of stability. From surface reports data are collected concerning the previous occurrence of thunderstorms.

The 850-mb. chart is used as a primary tool because shallow flow and isotherm wave patterns are usually represented better by that chart than by either the surface chart or the 700-mb. chart. In summer east of the Rockies a 700-mb. pressure ridge may exhibit only a minor cyclonic dip on its eastern side while a significant trough is apparent below at the 850-mb. level and on the surface chart. This is due to important temperature gradients that occur below the 700-mb. level in summer east of the Rockies. The surface chart is less representative than the 850-mb. chart because summer showers and thunderstorms in the Midwest are primarily higher level phenomena. The lower portion of the unstable layer is frequently near the 850-mb. level. Unfortunately such summer thunderstorm and precipitation patterns do not correspond well to classical concepts of precipitation around frontal wave cyclones.

Experience with several objective techniques demonstrated the necessity for stratification of different types of 850-mb. patterns. For example, an elongated north-south ridge is frequently slow-moving or stationary, effectively blocking the movement of pre-trough thunderstorms even though an area of such activity may be only a short distance away. Any classification of weather charts will, to a degree, be oversimplified and certain cases will tend to fit into more than one classification. The goal in classification has been to define fairly objectively the various types in order to reduce the number of borderline cases. The classification has been based to a large degree upon processes that have been related to thunderstorm occurrence and not merely upon relative positions of troughs and ridges as in the ordinary analogue procedure. This approach is expected to be useful to forecasters since they are accustomed to using primarily their understanding of the association of weather chart patterns with, in this case, thunderstorm activity, together with moisture and stability analyses and indirect aerology (analyses of clouds and previous thunderstorm occurrence). All of these factors are incorporated into this forecast guide.

The stability factor used is only a rough measure, the difference between 850-mb. and 500-mb. temperatures. The moisture factor is also a rough measure, the 850-mb. mixing ratio (dew point). Forecasters may be able to further eliminate certain no-thunderstorm situations by improving the selectivity of these factors by careful analyses of individual soundings and of individual flow patterns.

850-MB. CHART TYPES

The 850-mb. chart types (figs. 26–36) were derived from basic ideas established earlier in this thunderstorm study.

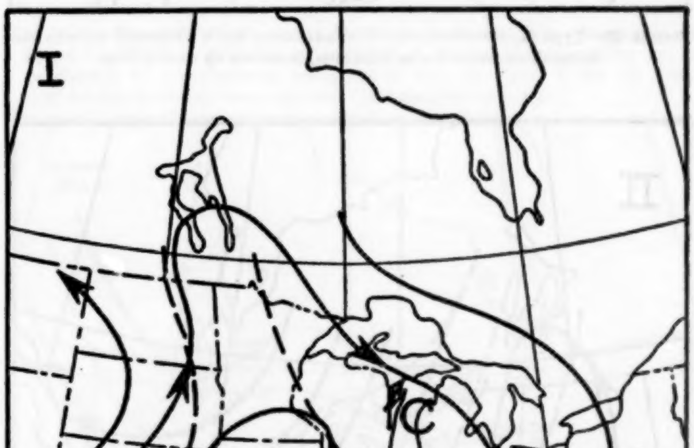

FIGURE 26.—Type I, 850-mb. chart. Post-trough cold advection. Streamlines are shown by solid lines, isotherms by dashed lines.

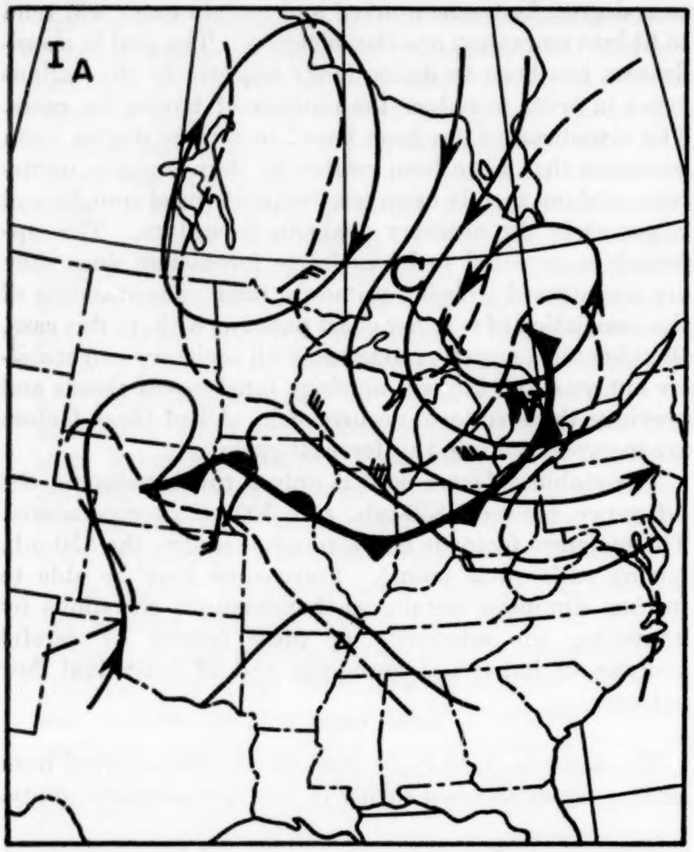

FIGURE 27.—Type IA, 850-mb. chart. Cold advection, but with frontal wave to west Streamlines are shown by solid lines, isotherms by dashed lines.

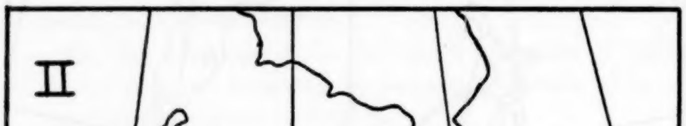

FIGURE 28.—Type II, 850-mb. chart. Northerly or northwesterly flow with neutral advection. Streamlines are shown by solid lines, isotherms by dashed lines.

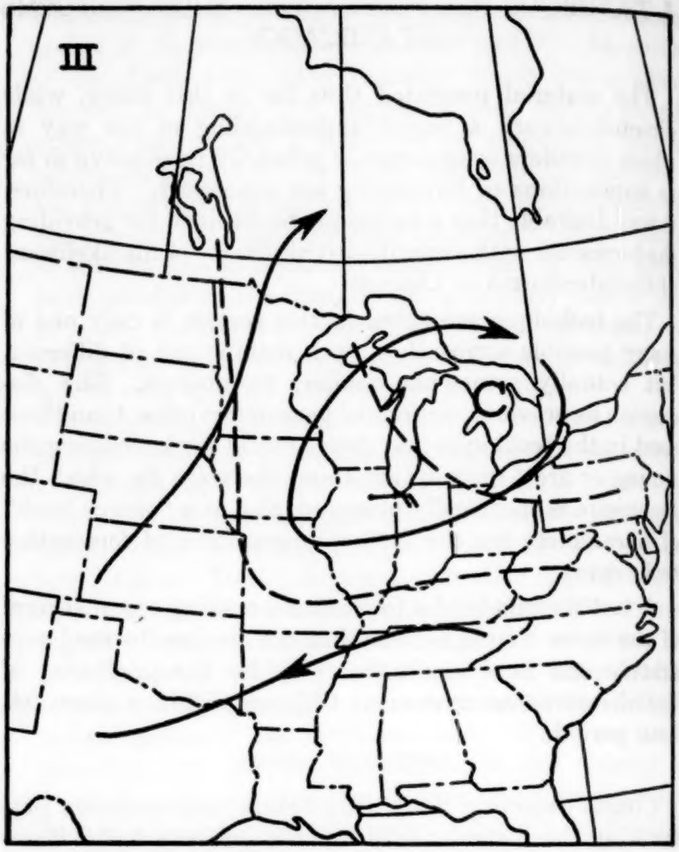

FIGURE 29.—Type III, 850-mb. chart. Closed anticyclone. Streamlines are shown by solid lines, isotherms by dashed lines.

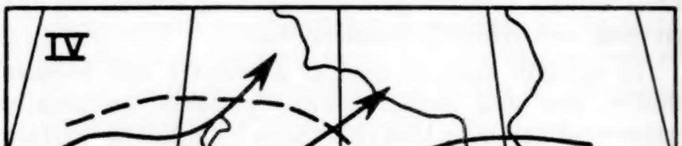

FIGURE 30.—Type IV, 850-mb. chart. Elongated ridge. Streamlines are shown by solid lines, isotherms by dashed lines.

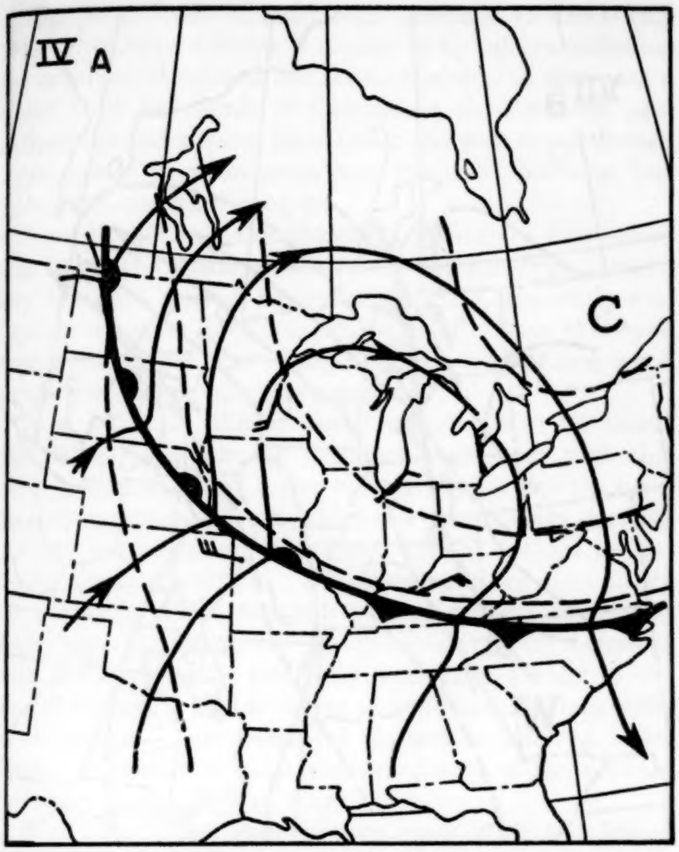

FIGURE 31.—Type IV$_A$, 850-mb. chart. Elongated ridge broken by warm front west or southwest of Chicago and with closed anticyclone to north. Streamlines are shown by solid lines, isotherms by dashed lines.

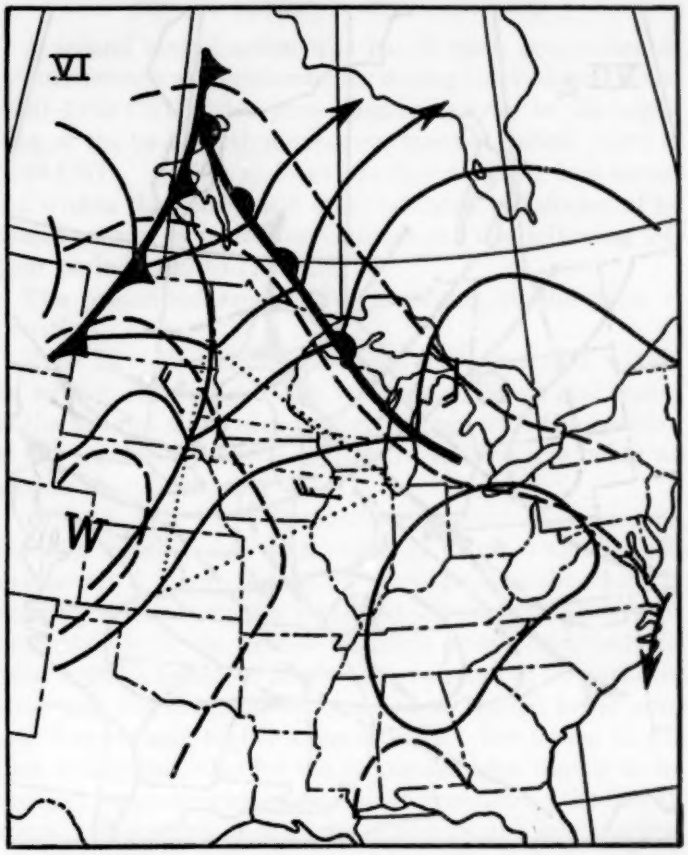

FIGURE 33.—Type VI, 850-mb. chart. Pre-trough warm advection. Streamlines are shown by solid lines, isotherms by dashed lines. Dotted triangle outlines area to be checked for thunderstorms during last 12 hours for Types V and VI. Thin dash-dot line illustrates "wave trajectory" line described on p. 185.

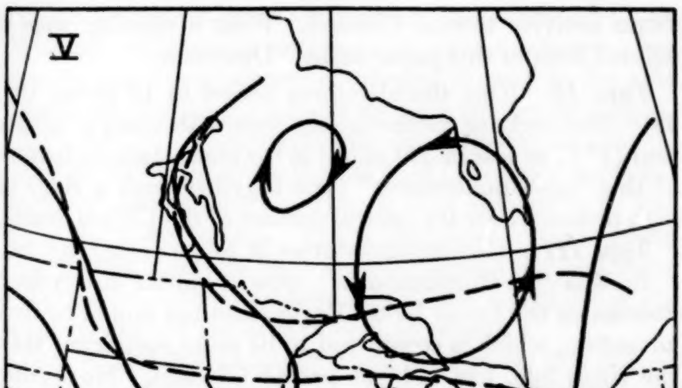

FIGURE 32.—Type V, 850-mb. chart. Westerly flow with neutral advection. Streamlines are shown by solid lines, isotherms by dashed lines.

FIGURE 34.—Type VII, 850-mb. chart. Pre-trough stagnant warm tongue. Streamlines are shown by solid lines, isotherms by dashed lines.

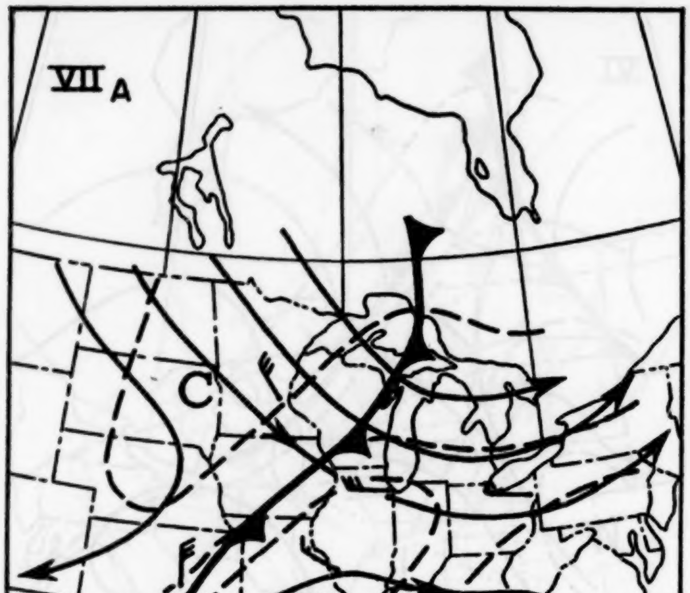

FIGURE 35.—Type VII$_A$, 850-mb. chart. Pre-trough warm tongue moving out. Streamlines are shown by solid lines, isotherms by dashed lines.

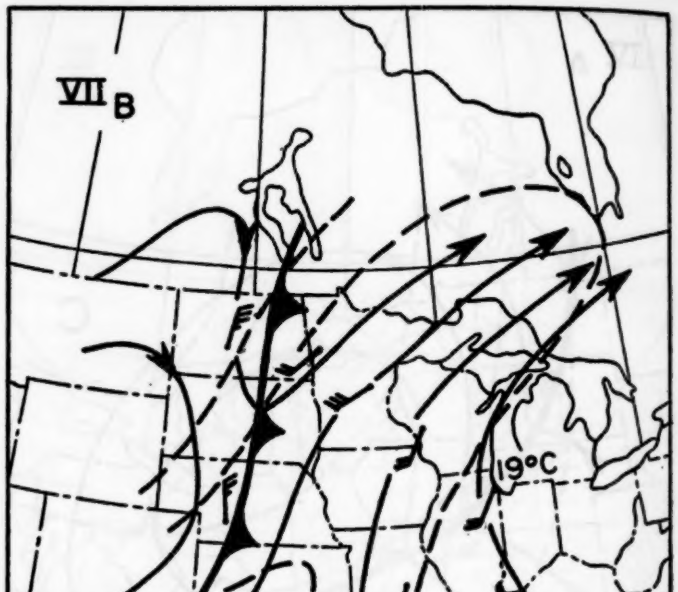

FIGURE 36.—Type VII$_B$, 850-mb. chart. Warm tongue west, neutral or cold advection from south or east on the east side of the warm tongue. Streamlines are shown by solid lines, isotherms by dashed lines.

The derivation period from which the chart types were chosen, was that for July and August 1945, and June, July, and August, 1946 and 1947; data for the summer of 1948 were reserved for an independent test. Tests have also been made for later years. The various types of patterns were taken from and are representative of charts for the 1000 CST radiosonde observation as compared with the occurrence or nonoccurrence of thunderstorms during the following 24-hour period 1230 to 1230 CST.

Type I. (No thunderstorms in 33 cases during the derivation period) (fig. 26).—This type is one of the most frequent "no-thunderstorm" situations. It is characterized by post-trough cold advection at Chicago, usually with a north-south ridge over the Central States. The air mass is relatively cool and dry, but not always stable. On a few occasions in late summer, cool air masses crossing the Great Lakes have become unstable giving a few widely scattered thunderstorms, but mostly north of Chicago.

Type I$_A$. (One thunderstorm period in three cases) (fig. 27).—While this subtype is infrequent, it calls attention to the necessity for a careful check of Type I situations for possible modifications that may contribute to thunderstorm formation. Cold advection predominates at Chicago in this subtype, but with a frontal wave to the west thunderstorms may quickly redevelop in the Chicago area. The cross pattern must be oriented in such a way as to suggest possible wave movement from the area of thunderstorm activity toward Chicago. Such a steering zone is defined later in this paper under "Discussion."

Type II. (One thunderstorm period in 14 cases) (fig. 28)—Northerly or northwesterly flow with neutral advection (1° C. or less in 300 miles) is the characteristic feature of this "no-thunderstorm" type together with a ridge of high pressure over the central portion of the United States.

Type III. (No thunderstorms in seven cases) (fig. 29). —In this "no-thunderstorm" type a closed anticyclone dominates the Great Lakes Region and the line of neutral advection, which is considered to be more significant than the ridge line, has not yet passed Chicago. No frontal waves are present immediately south or west of Chicago.

Type IV. (One thunderstorm period in 27 cases) (fig. 30).—The elongated ridge in this "no-thunderstorm" type is usually warm and slow-moving. Again the position criterion is the neutral advection line. If it is past Chicago, a better chance exists for an area of thunderstorms to glide eastward or southeastward into the Chicago area within the next 24 hours. Of course if the line of neutral advection is not yet past as in this type, opportunities for thunderstorms to reach the Chicago area are more limited. In this type of situation thunderstorms may be occurring over parts of Iowa, Minnesota, and Wisconsin and still not reach Chicago during the next 24 hours due to the blocking action of the ridge.

Type IV_A. (One thunderstorm period in 15 cases) (fig. 31).—This ridge subtype is similar to the above including the criterion of neutral advection line, but in this case a closed High lies north of Chicago in the northern part of the ridge and a warm front lies to the west or southwest. Again many thunderstorms may occur to the west but make little eastward progress.

Type V. (Three thunderstorm periods in five cases) (fig. 32).—The predominant feature of this type is westerly flow with neutral advection, which is frequently susceptible to wave development, especially since this type occurs with short wave length to the rear of one weak trough and in advance of another.

Type VI. (27 thunderstorm situations in 74 cases) (fig. 33).—More summer thunderstorms occur with this pattern than with any other, but the type is also the most frequent summer pattern, which does not greatly simplify the forecast problem. The predominant feature is pre-trough warm advection. Thunderstorms are more likely the second or third day this pattern or type is present rather than the first day. On the first day, the degree of cross pattern may be relatively weak immediately to the rear of a ridge. Also moisture may be lacking since sufficient time may have not yet elapsed to allow a moist tongue to thread its way northward around the western periphery of the High or ridge.

Type VII. (Ten thunderstorm cases in 30) (fig. 34).—Another type which accounts for a number of thunderstorm situations is the pre-trough stagnant warm tongue type in which the warm tongue is located over Chicago but with no important warm advection (less than 1° C. in 300 miles). The warm tongue is described as stagnant because no important current is oriented normal to the axis of the warm tongue to rapidly displace the warm tongue.

Type VII_A. (No thunderstorms in 15 cases) (fig. 35).—In this subtype the warm tongue over Chicago is not stagnant, but moving, with a zone of cold advection to the rear of the warm tongue. If any thunderstorms are going to occur with this type, they must occur near the beginning of the period before the influence of the warm air is replaced by that of the area of cold advection.

Type VII_B. (One thunderstorm in 23 cases) (fig. 36).—Another "no-thunderstorm" subtype has a warm tongue as a predominant feature, but the warm tongue is centered west of Chicago. This type of warm tongue shows little eastward movement and has neutral or cold advection from the east or south on the east side of the warm tongue.

Following classification, the charts were stratified to eliminate predominantly "no-thunderstorm" types. Only cases corresponding to the following types were retained for further examination:

- I_A. Cold advection but active wave and thunderstorm west or southwest.
- V. Neutral advection, westerly flow.
- VI. Pre-trough warm advection.
- VII. Stagnant warm tongues.

PREVIOUS OCCURRENCE OF THUNDERSTORMS

A second stratification was based upon occurrence or nonoccurrence of thunderstorms during the 12-hour period 0030–1230 CST within prescribed areas prior to the beginning of the 24-hour thunderstorm forecast period (1230 to 1230 CST). Unless at least one thunderstorm had occurred within the period and area indicated, a forecast of no thunderstorm is made for Chicago for the following 24-hour period 1230 to 1230 CST.

The prescribed areas differ according to the type of situation.

Type I_A. Thunderstorms must have occurred within an equilateral triangle with vertex at Chicago and center of the base on a line connecting Chicago with the position of the surface wave, the altitude of the triangle being no greater than 400 miles.

Types V and VI. Thunderstorms must have occured within a steering zone with vertex at Chicago and defined as follows: A "wave trajectory" is outlined on the chart by drawing a line from the vertex at Chicago parallel to or concentric with the nearest diagonal across cross-pattern cells, (100-foot contour height intervals and 5° C. isotherm intervals) the diagonal being directed toward lower contour heights and higher temperatures. See figure 33 for such a diagonal, also for the triangular area that is to be checked for occurrence of thunderstorms during the last 12 hours. The width of the zone at any point along the trajectory is equal to the distance along the trajectory from Chicago. A maximum distance along the trajectory for the zone is either the distance to the first neutral advection line associated with an out-of-phase trough, or 600 miles, whichever is less.

Type VII. Stagnant warm tongues are by definition not susceptible to important steering patterns. Therefore, for these cases an area within 200 miles radius of Chicago is used to check for previous occurrence of thunderstorms.

STABILITY AND MOISTURE

Following the second stratification, which is based upon the previous occurrence of thunderstorms, a scatter diagram was prepared, the coordinates of which are (1) the difference between 850-mb. temperature and 500-mb. temperature and (2) the 850-mb. mixing ratio (dew point) (fig. 37).

The highest 850-mb. mixing ratio (dew point) value within a given distance, which depends upon the type, is selected together with 850-mb. and 500-mb. temperatures taken at that same point. A greater distance is not used since moisture values at a given level are notoriously subject to change due in part to vertical motion in the pre-trough area. A somewhat longer distance might be non-representative due to subsidence drying effects east of the Rockies. Moisture values are read at the relatively low 850-mb. level because horizontal convergence in the pre-trough area is likely to deepen the air column making the lower-level values more representative of the air column

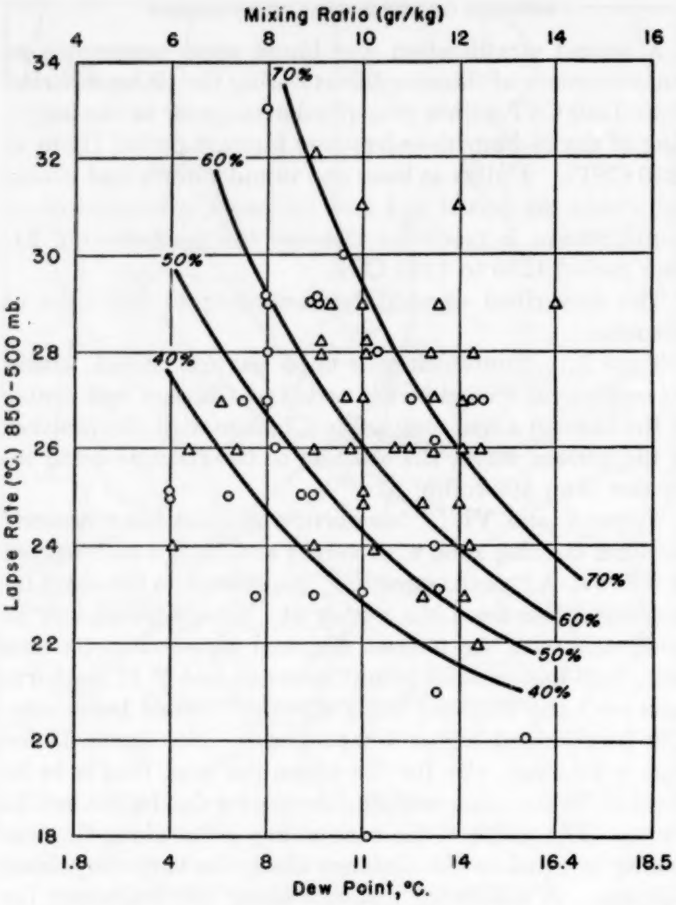

Figure 37.—Stability-moisture scatter diagram for showing relative frequency of thunderstorms for cases not separated out in two stratifications. Prepared from derivation data for June 1946, 1947, and July-August 1945, 1946, 1947. Triangle is thunderstorm, circle is no-thunderstorm.

up to the middle-type cloud level than would a moisture value initially read at a higher level. The lapse rate is not taken all the way to the surface because few Chicago thunderstorms apparently originate with steep lapse rates all the way to the surface, but to a greater degree with steep lapse rates above the 850-mb. level.

The moisture and lapse rate values are interpolated from the charts at the following points for the various types:

Type I_A. The highest moisture value within 250 miles of Joliet and measured toward the surface position of the frontal wave is selected together with 850-mb. temperature and 500-mb. temperature taken at that same point.

Types V and VI. The highest moisture value and corresponding temperatures are taken within 250 miles of Joliet along the "wave trajectory," which is defined in the previous section.

Type VII. Joliet values are used in the stagnant warm tongue situations.

These measures of stability and moisture were chosen following experimentation with many others including equivalent potential temperature, equivalent temperatures, condensation pressures, etc. The simple measures chosen showed as good or better selectivity (following the initial stratifications) than the more complex forms. The scatter diagram for the derivation period is found in figure 37.

A careful examination of this distribution indicates that better skills may be achieved by use of a 40-percent relative frequency line rather than a 50-percent line as a criterion for a categorical forecast. Relatively few cases are found below the 40-percent line due to the two previous screenings.

DISCUSSION

In this subsection some of the more important influences as applied to chart classification and stratification are discussed.

In the modified ridge Type IV_A, a case was found with strong southerly flow and warm frontogenesis to the west and southwest of Chicago. Thunderstorms reached Chicago late in the 24-hour period in this usually "no-thunderstorm" general type. This situation occurred June 14, 1946.

The example of the pre-trough warm advection type is a first day of this type which frequently persists 2 or 3 days. The first day (as stated above) is less favorable for thunderstorm activity than second- or third-day patterns, which usually are associated with more moisture than is present on the first day. However, in the first-day example shown, a thunderstorm occurred.

In Type VII_A one must watch for the formation of a secondary trough since in that case a small area of cold advection may not displace the warm tongue by any great amount before the secondary trough again draws the warm tongue northward. Frontogenesis in a nearly stationary trough (even though northerly winds flow into the trough) can also contribute to thunderstorm formation in this usually "no-thunderstorm" type. In this case the center of the warm tongue moves very little (June 11, 1948).

In Type VII_B one must watch for thunderstorms occurring in a relatively small area of convergence which moves northward in the southerly flow.

TESTS

A check of the skill of categorical separation of thunderstorm and no-thunderstorm cases for the derivation period gave a skill score of .67 (see table 5).

A test on independent data was conducted making use of data for the summer of 1948. The classification of cases by type is given in table 6.

Following the second stratification based upon previous occurrence of thunderstorms, 36 cases remained, 17 of them thunderstorm cases. In plotting lapse rate versus mixing ratio points for these cases and copying the criterion line from the derivation scatter diagram, 8 of the no-thunderstorm cases were separated out (fig. 38). One

Table 5.—*Test of thunderstorm forecasting technique for the derivation period, June 1946 and 1947 and July and August 1945, 1946, 1947*

		Indicated		
		Thunderstorm	No thunderstorm	Total
Observed	Thunderstorm	38	7	45
	No thunderstorm	20	181	201
	Total	58	188	246

Table 6.—*Classification of 850-mb. patterns on individual days, June, July, and August 1948. Underlined dates refer to thunderstorm cases.*

	June	July	August
Type I. Cold advection	7	23	1
	13	27	3
	16	30	4
	19	------	13
	30	------	18
Type I_A. With wave west or southwest	$\underline{5}$	------	2
	15	------	9
	------	------	$\underline{12}$
Type II. Neutral advection-northwest flow	8	6	11
	9	26	------
	29	31	------
Type III. Closed anticyclone	1	------	------
	2	------	------
Type IV. Blocking ridge	3	7	5
	17	8	6
	------	19	14
	------	24	15
	------	28	19
	------	------	20
	------	------	30
	------	------	31
Type IV_A. With warm front west to southwest	20	14	------
Type V. Neutral advection-westerly flow	24	18	------
Type VI. Pre-trough warm advection	4	1	7
	6	4	8
	14	5	$\underline{10}$
	18	15	$\underline{16}$
	21	$\underline{20}$	$\underline{17}$
	25	$\underline{21}$	21
	26	$\underline{25}$	22
	$\underline{27}$	$\underline{29}$	23
	------	------	28
	------	------	$\underline{29}$
Type VII. Warm tongue stagnant in vicinity of Chicago	10	2	------
	$\underline{22}$	$\underline{10}$	------
	$\underline{23}$	$\underline{11}$	------
	28	$\underline{12}$	------
	------	13	------
	------	$\underline{22}$	------
Type VII_A. Warm tongue over station but moving rapidly	$\underline{11}$	16	------
	12	17	------
Type VII_B. Warm tongue west with neutral or cold advection from east or south	------	3	24
	------	9	25
	------	------	26
	------	------	27

thunderstorm had been lost in the first stratification, type classification, when a warm tongue which was classified as moving out (Type VII_A), appeared again in the Chicago area with thunderstorms along a trough associated with a weak warm front.

Skill computed for this test was .66, which is perhaps high due to sampling errors since test skills usually can be expected to be somewhat lower than derivation skills. The results are summarized in table 7.

Table 7.—*Test of the thunderstorm forecasting technique for the test period, summer 1948*

		Forecast		
		Thunderstorm	No thunderstorm	Total
Observed	Thunderstorm	17	1	18
	No thunderstorm	11	63	74
	Total	28	64	92

The cases with the type of error in which thunderstorms were forecast by the above technique but none observed at Chicago Airport are tabulated below with remarks on observed weather:

June 4, 1948	Shower at Chicago, thunderstorm at surrounding stations.
June 6, 1948	Shower at Chicago, thunderstorm at Rockford.
June 18, 1948	Shower at Chicago, thunderstorm at Muskegon.
June 21, 1948	Thunderstorms south and west, and early in second 24-hour period at Chicago.
June 25, 1948	Thunderstorms south and northwest, Terre Haute and La Crosse.
July 4, 1948	Shower at Chicago, thunderstorms at surrounding stations.
July 5, 1948	Isolated thunderstorms, Green Bay and St. Louis.
July 13, 1948	Shower at Chicago, thunderstorms south and west.
July 15, 1948	Showers south.
Aug. 21, 1948	Thunderstorm at Green Bay.
Aug. 28, 1948	Cumulonimbus at Chicago.

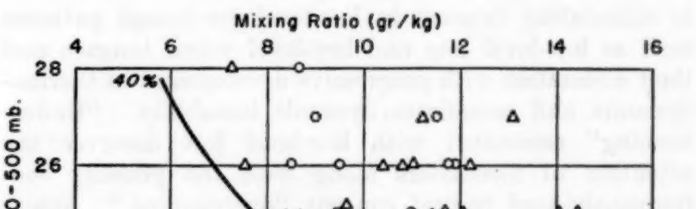

Figure 38.—Test cases (June, July, August 1948) on stability-moisture scatter diagram. Forty percent relative frequency line is from figure 37. Triangle is thunderstorm, circle is no-thunderstorm.

In about half of these no-thunderstorm cases (at Chicago) a forecaster would have felt well justified in having issued a thunderstorm forecast for Chicago.

Other situations which were *typed* as favorable but which were separated out by the 40 percent line on the lapse rate-mixing ratio scatter diagram were as follows:

June 14, 1948	Thunderstorms southwest, also north.
June 15, 1948	Showers in southern Illinois.
June 28, 1948	Showers with an isolated thunderstorm at Milwaukee.
July 1, 1948	Lightning at Chicago.
July 18, 1948	Few widely scattered showers.
Aug. 2, 1948	Scattered showers.
Aug. 9, 1948	Thunderstorms north.
Aug. 22, 1948	Thunderstorms north.

In two or three cases here the forecaster probably would have felt justified in having issued a thunderstorm forecast for Chicago. But an examination of these cases together with the previous cases shows less justification for thunderstorm forecasts in the latter group as a whole, than with the former group, which is consistent with the probabilities as indicated on the scatter diagram.

The forecast of no thunderstorm for the one error in which a thunderstorm occurred, was as previously mentioned a case in which a warm tongue had been typed as moving out, but which persisted in the vicinity of Chicago. This forecast error was mostly due to an error in classifying the chart.

Subsequent tests on independent data during June through August, 1949, 1950, and 1951 are summarized in table 8.

TABLE 8.—*Tests of the thunderstorm forecasting technique on independent data, June-August 1949, 1950, 1951*

1949		Forecast: Thunderstorm	Forecast: No thunderstorm	Total	
Observed	Thunderstorm	14	3	17	Skill score=.44
	No thunderstorm	18	57	75	
	Total	32	60	92	

1950		Forecast: Thunderstorm	Forecast: No thunderstorm	Total	
Observed	Thunderstorm	11	3	14	Skill score=.44
	No thunderstorm	15	63	78	
	Total	26	66	92	

1951		Forecast: Thunderstorm	Forecast: No thunderstorm	Total	
Observed	Thunderstorm	15	5	20	Skill score=.52
	No thunderstorm	12	60	72	
	Total	27	65	92	

SUMMARY

This paper is offered not as a final solution of thunderstorm forecasting problems, but rather as a digest of a number of years' experience with these midwestern summer patterns. The author hopes that he has succeeded in stimulating interest in low-level pre-trough patterns such as low-level jets and low-level warm tongues and their association with progressive development of thermodynamic and sometimes dynamic instability. "Underrunning" associated with low-level jets deserves the attention of forecasters along with the possibly too-frequently-used frontal concept "overrunning." Attention is also directed to the contribution of the semipermanent (in summer) hub of warm air in the southwestern United States toward the development of cross patterns and the movement of associated areas of thunderstorm activity.

Further work must be done to improve our understanding of the forecasting significance of large vertical and horizontal wind shears.

Later work may make possible some useful associations of low-level patterns to high-level (near tropopause) jet maxima and minima, which are of considerable interest for forecasting during the winter season.

Work will also be undertaken with reference to the objective technique for forecasting thunderstorms at Chicago, especially to simplify the classification of patterns and to introduce other possibly significant parameters.

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THE WEATHER AND CIRCULATION OF OCTOBER 1952 [1]

The Driest Month on Record in the United States

Jay S. Winston

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

THE DROUGHT

Over the United States as a whole October 1952 set a new record by a wide margin as the driest month ever observed. This month's average rainfall for the nation was 0.54 inches, only 26 percent of normal, and the least precipitation on both an absolute and relative scale for all months in the long Weather Bureau record dating from 1886. Figure 1 and Charts II and III reveal the details of the October drought over the United States. Along and west of the Mississippi Valley many States had precipitation averaging less than 10 percent of normal. In fact, a large portion of this region, comprising one-third or more of the total area of the United States, went without any measurable rainfall during the entire month. At Salt Lake City, Utah, this was the first October in 79 years of record without any precipitation and 62 consecutive rainless days passed before precipitation finally fell in that city on November 13. Minneapolis-St. Paul, Minn., with total October rainfall of only 0.01 inch, had the driest October since 1857. Louisiana and Mississippi suffered the second longest rainless period on record (45 days) ending on November 6. Similar records were set at many other stations in this area. East of the Mississippi, although precipitation was generally not so deficient as in the West, most States reported less than 50 percent of their normal October rainfall. Florida was the only State in the nation where October rainfall was in excess of the normal amount.

The drought over most of the Nation became very pronounced in late September [1] and continued through the first week of November. However, in many areas of the Midwest and South this period was the culmination of a much longer period of generally deficient precipitation extending as far back as the spring of 1952 [2, 3]. A tabulation of precipitation amounts and their departures from normal at a selected group of stations (table 1) shows the extent of the cumulative deficiency of precipitation in the 3- and 5-month periods ending in early November.

[1] See Charts I–XV following p. 202 for analyzed climatological data for the month.

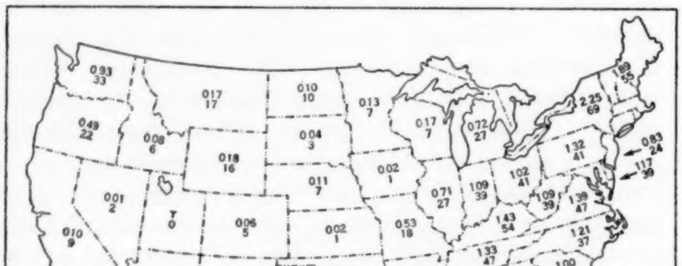

FIGURE 1.—Total inches and percentage of normal precipitation by States, October 1952. (From U. S. Weather Bureau, *Weekly Weather and Crop Bulletin National Summary* for week ending November 18, 1952.)

TABLE 1.—*Total precipitation and departures from normal (inches) during extended drought period* [1]

Station	12 weeks ending Nov. 4, 1952		22 weeks ending Nov. 4, 1952	
	Total	Departure	Total	Departure
Arkansas				
Fort Smith	3.52	−4.93	7.49	−8.52
Little Rock	3.14	−5.48	8.39	−8.39
Indiana				
Evansville	3.79	−5.95	11.32	−4.40
Kansas				
Concordia	1.77	−4.71	4.77	−10.68
Dodge City	2.25	−2.51	3.96	−8.20
Goodland	1.46	−3.11	5.73	−5.29
Wichita	2.07	−5.70	8.45	−7.96
Kentucky				
Louisville	4.84	−3.60	11.54	−5.23
Louisiana				
Shreveport	.95	−6.60	6.95	−8.37
Mississippi				
Vicksburg	2.32	−5.69	4.47	−13.06
Meridian	1.41	−5.60	6.18	−12.96
Nebraska				
Lincoln	2.94	−4.17	15.37	−0.96
North Platte	1.88	−1.94	6.66	−3.79
Valentine	.39	−3.25	4.75	−5.65
Oklahoma				
Oklahoma City	.82	−6.91	5.89	−9.24
Texas				
Abilene	2.34	−4.56	3.10	−9.39
Amarillo	.84	−4.96	3.87	−8.73
Austin	2.32	−5.81	4.89	−7.90
Big Spring	2.66	−3.58	3.37	−7.41
Del Rio	.02	−6.19	.66	−10.87
Fort Worth	.55	−6.76	1.55	−12.38
Laredo	.53	−6.15	5.15	−5.37

[1] From *Weekly Weather and Crop Bulletin, National Summary* for week ending Nov. 4, 1952.

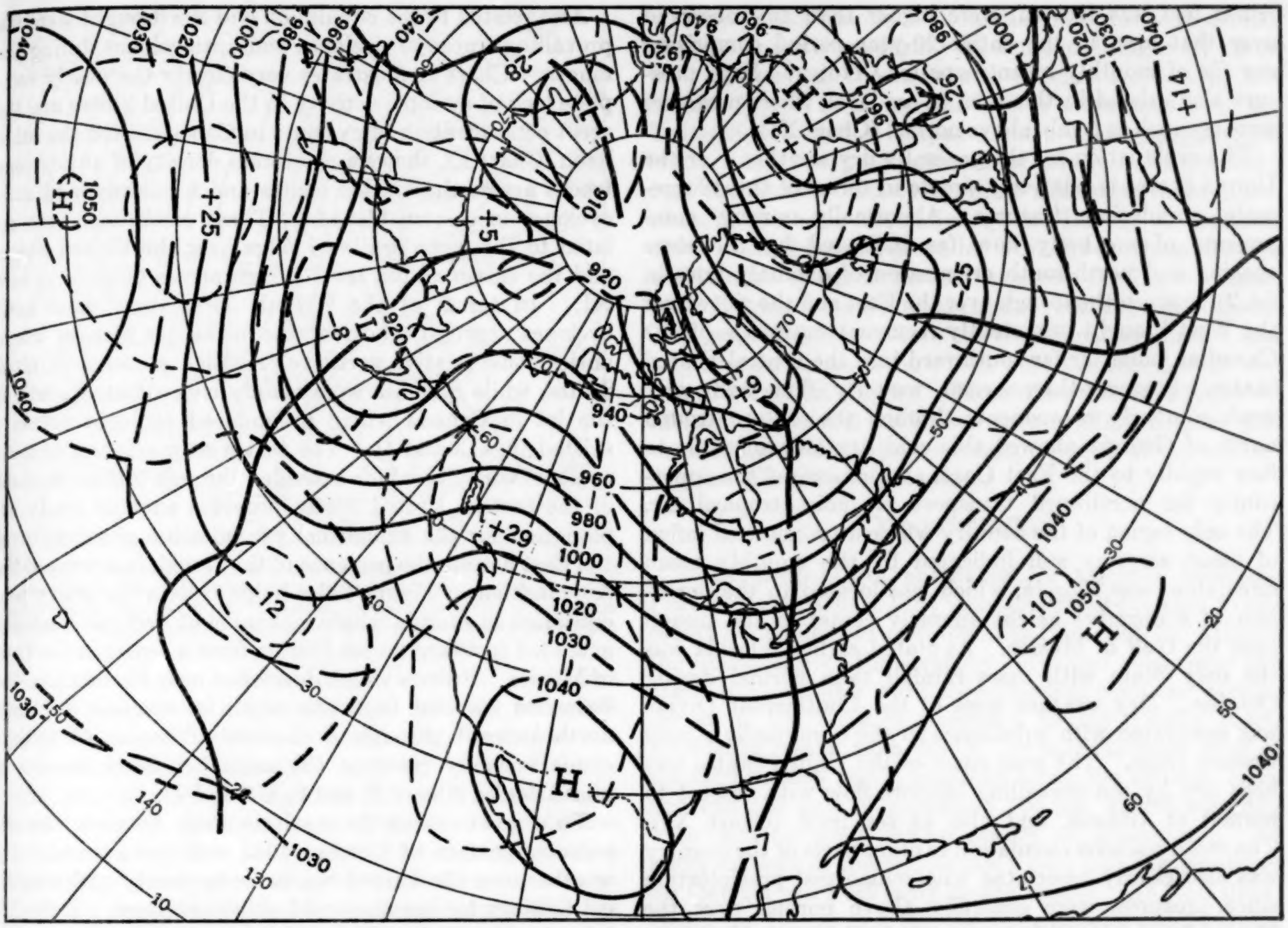

FIGURE 2.—Mean 700-mb. chart for the 30-day period September 30–October 29, 1952. Height anomalies at 100-foot intervals are shown by short dashed lines and anomaly centers are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

There were several serious consequences of this extensive and severe autumn drought as it persisted into late October. Forest, grass, and brush fires were reported in more than half of the States east of the Rocky Mountains. Thousands of square miles of grass and timber lands were scorched as many of these fires became uncontrolled. Shenandoah National Park in Virginia as well as many State and National forests were closed to the public as the fire hazard became extremely critical late in the month. Heavy smoke palls resulted from these extensive fires and lingered over many central and eastern sections of the country both night and day during periods of pronounced vertical atmospheric stability in the second half of October. Smog from Louisiana prairie fires lowered the visibility so much that traffic was disrupted in New Orleans on the 27th. Water shortages developed in many central sections of the nation as wells, ponds, and streams began to dry up. Planting and germination of the winter wheat crop were seriously retarded by the drought, and prospects for the crop were very poor at month's end.

RELATED CIRCULATION FEATURES

The middle and upper tropospheric circulation over North America and vicinity was dominated by a sinusoidal wave pattern of large amplitude consisting of an abnormally strong ridge over the mountains of western North America flanked by two pronounced troughs, one over the eastern Pacific, the other over eastern North America (fig. 2 and Charts XIII–XV). This is the same basic pattern which first became established during the second half of September [1], and prevailed with very little variation from day to day or week to week throughout October. The western ridge was the most prominent feature of this pattern since mean 700-mb. heights were more than 200 feet above normal over a broad region extending from the Yukon to southern Utah. Heights over British Columbia, where a maximum anomaly of

+290 feet was located, were higher than any observed over that area in the entire 20-year period comprising our file of monthly mean maps for October. High pressure also existed in this area at sea level, where pressures were as much as 6 mb. above normal (Chart XI).

The explanation for the generally dry weather over the United States is relatively simple in terms of these large-scale circulation features. Abnormally strong components of northerly flow (as indicated by the close spacing and north-south orientation of anomaly lines in fig. 2) between the trough over the East and the ridge over the West brought persistently recurrent outbreaks of dry Canadian polar air far southward into the central United States. Stronger-than-normal westerly flow and very weak southerly components through the eastern trough north of Georgia allowed this cold dry Canadian air to flow rapidly to the East Coast and minimized the opportunity for northward transport of moist tropical air. The only region of the country where a pronounced influx of moist air was well indicated by the monthly mean circulation was Florida, which was located to the northeast of a negative height anomaly center in the trough over the Gulf of Mexico. As stated earlier, Florida was the only State with more rainfall than normal during October. Dry weather west of the Continental Divide was associated with subsidence in the abnormally strong western ridge. The west coast of the United States was kept dry by the prevailing offshore flow with respect to normal at 700-mb. and also at sea level (Chart XI). The mean sea level circulation in other parts of the country was also clearly associated with subnormal precipitation since pressures were generally above normal over the Nation in and around an extended ridge stretching from British Columbia southeastward to the Appalachians.

Also related to the circulation and the drought were the prevailing tracks of cyclones and anticyclones during the month. Chart X illustrates very clearly the nearly complete lack of cyclonic activity in the United States and the great concentration of cyclones in Canada. On the other hand, Chart IX shows a maximum density of anticyclone tracks across the United States and a minimum of anticyclones in eastern Canada. These conditions were related to the mean sea level ridge over the United States and the east-west sea level trough across Canada (Chart XI). In terms of the 700-mb. circulation most anticyclones traveled south of the mean jet stream where anticyclonic relative vorticity prevailed across the United States, while cyclones were mainly concentrated north of the jet in Canada where pronounced cyclonic vorticity existed (figs. 3 and 4). The east-west maximum of anticyclonic vorticity which extended through middle sections of the eastern United States provides another ready explanation for the subnormal precipitation observed over the East despite the presence of the trough just west of the Appalachians. Figure 4 also helps explain the heavy precipitation in Florida where a channel of cyclonic vorticity extended eastward across Florida from a center in the Gulf of Mexico. Storms which developed near Florida and the Bahamas traveled from this region of cyclonic vorticity northeastward through a distinct minimum of anticyclonic vorticity reaching the main belt of westerlies in mid-Atlantic (Chart X and figs. 3 and 4).

To a great extent these relationships between the circulation pattern of October 1952 and the generally dry weather over the United States tie in closely with empirical findings for previous cold season regimes. Tannehill [4] pointed out that November droughts over the nation are generally associated with high surface pressure in the

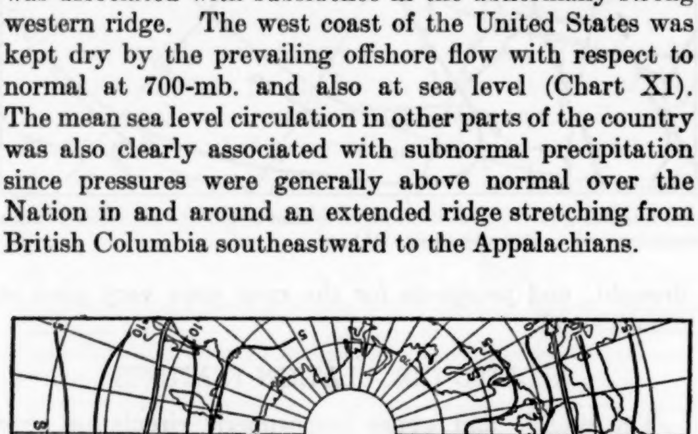

FIGURE 3.—Mean horizontal geostropic wind speed at 700-mb. for the 30-day period September 30–October 29, 1952, in m sec^{-1}. Arrowed line indicates the major axis of maximum wind speeds (jet). Centers of maximum and minimum wind speed are labeled "F" and "S" respectively.

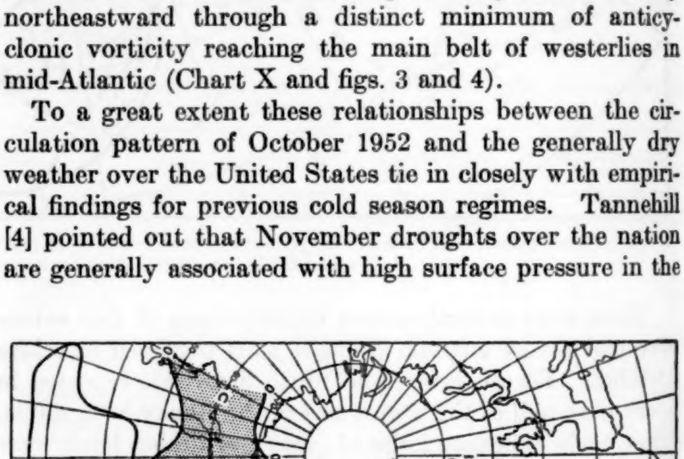

FIGURE 4.—Mean relative geostropic vorticity at 700-mb. for the 30-day period September 30–October 29, 1952 in units of 10^{-4} sec^{-1}. Areas of cyclonic vorticity are shaded and labeled "C" at centers of maximum vorticity. Areas of maximum anticyclonic vorticity are labeled "A".

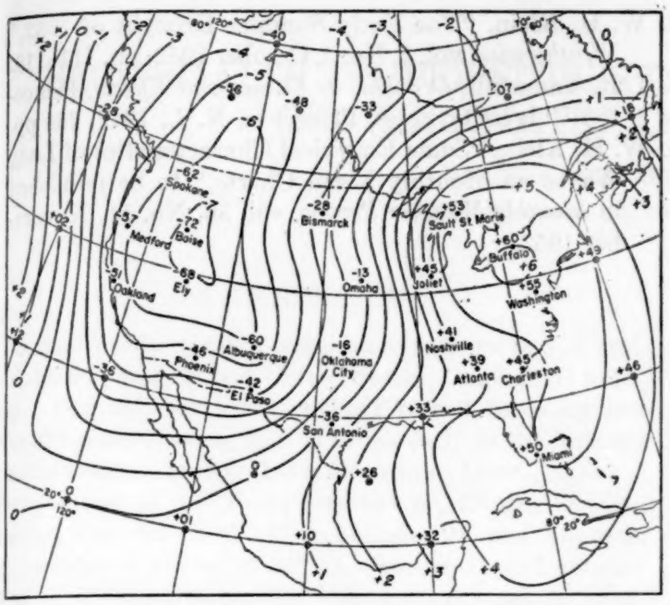

Figure 5.—Correlation field patterns of mean monthly 700-mb. height anomalies at indicated locations vs. monthly rainfall averaged over the United States as a whole for winter months from 1939 to 1952. Correlation coefficients are shown in hundredths and correlation isopleths are labeled in tenths (decimal points omitted). (*After Stidd.*)

Great Basin region. Recent work by C. K. Stidd has clearly demonstrated that subnormal monthly precipitation in the United States as a whole during the cold season is closely related to positive monthly mean 700-mb. height anomalies in the West, as well as negative height anomalies in the East. Figure 5, which Mr. Stidd has kindly made available to the author prior to publication of his work, demonstrates these relationships quite clearly. This figure shows the field of linear correlation coefficients between over-all United States rainfall amounts for monthly periods and monthly 700-mb. height anomalies at the indicated locations. The presence of high negative correlation in the West shows that positive height anomalies in that region favor dry weather in the nation as a whole, while negative height anomalies favor wet weather. Heights in the East are also of great importance in determining nationwide precipitation as indicated by the large area of positive correlation there. These two areas of maximum positive and negative correlation taken together essentially reflect the importance of meridional wind components in determining United States precipitation, and are also related to the basic wave pattern over North America. In a paper to be published in the next issue of this *Review* Klein [5] has shown that the typical wave spacing over North America on monthly mean 700-mb. charts during the cold season calls for a trough in eastern North America when a pronounced ridge is located in the West and vice versa, as might be anticipated from vorticity considerations. In addition he has noted that either one of these patterns (i. e., trough in West and ridge in East, or ridge in West and trough in East) is more favored during the winter season than any other intermediate pattern.

Some of this October's circulation features were similar to those in existence during the summer drought [3] which was confined to southern and eastern sections of the country [3]. These were the lack of storminess over the United States, well-developed westerlies along the northern border, and the predominance of anticyclonic vorticity over the Nation. However, there were some large differences in the basic circulation type. During the summer above normal heights prevailed over the northeast Pacific and in more or less zonal fashion across the United States while heights were below normal across most of Canada. This is quite different from the meridional circulation and height anomaly patterns which were associated with this month's drought (fig. 2). These differences are probably related to seasonal variations in prevailing lengths and amplitudes of long wave patterns, strength of the westerlies, and air mass distributions.

TEMPERATURES

Mean temperature anomalies for October over the United States (Chart I–B) were also closely related to the month's well-defined circulation pattern (fig. 2). Under the dominance of the strongly developed ridge over the West, temperatures were above normal from the eastern slopes of the Rockies westward to the Pacific coast. Anomalies greater than +6° F. prevailed through most of the Great Basin region generally along the 700-mb. ridge line and the axis of maximum 700-mb. height anomaly from Arizona north-northwestward to Washington. At many stations in this region new record high temperatures for October were set early in the month. At Red Bluff, Calif., on the 1st and 5th the thermometer climbed to a record of 102° F., while at Yuma, Ariz., 109° F. was recorded on the 4th.

From the Great Plains eastward to the Atlantic coast this month's weather was unusually cold. This was closely related to the stronger-than-normal northerly flow between the western ridge and eastern trough which led to frequent outbreaks of cold Canadian polar air far south into most of the country east of the Rockies. The coldest weather with respect to normal occurred in the Mississippi and Ohio Valleys and the Upper Lakes, areas which were generally to the west of the mean upper level trough. As mentioned earlier the stronger-than-normal westerly flow at 700-mb. through this trough allowed the cold polar air to move to the East Coast with little chance for warm air to be advected northward at the surface. An unusually large number of cold polar highs emanated from Canada and traversed the eastern three-fourths of the United States (Chart IX) bringing new early season minimum temperature records to many stations and abnormally early frosts to the Southern States. The adjoining article by Parry and Roe presents details of record low temperatures on October 20–22.

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RECORD LOW TEMPERATURES IN THE MID-ATLANTIC AND EAST CENTRAL STATES, OCTOBER 20–22, 1952

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INTRODUCTION

Unusually cold weather engulfed a large portion of mid-Atlantic and east central United States, October 20 to 22, 1952. The cold outbreak yielded record breaking low minimum temperatures (fig. 1) for so early in the autumn at many places. Among these, Rochester, Minn., reported a temperature of 12° F. on October 20, Elkins, W. Va., observed a minimum of 11° on October 21, and Augusta, Ga., reported a lowest of 33° on October 21 and another lowest of 30° on October 22. The record breaking minimum of 23° which occurred at Dayton, Ohio, on October 21, was accompanied by a sea level pressure of 1037.6 mb., a new record for highest sea level pressure at that station.

The cold spell was unique because of its intensity rather than its synoptic pattern. As recently as October 18, 1948, a similar synoptic situation also set a few new temperature records. During October 1952, several of the 1948 records were superseded and a number of records established in former years were broken. It is our purpose here to discuss the synoptic aspects of the 1952 situation.

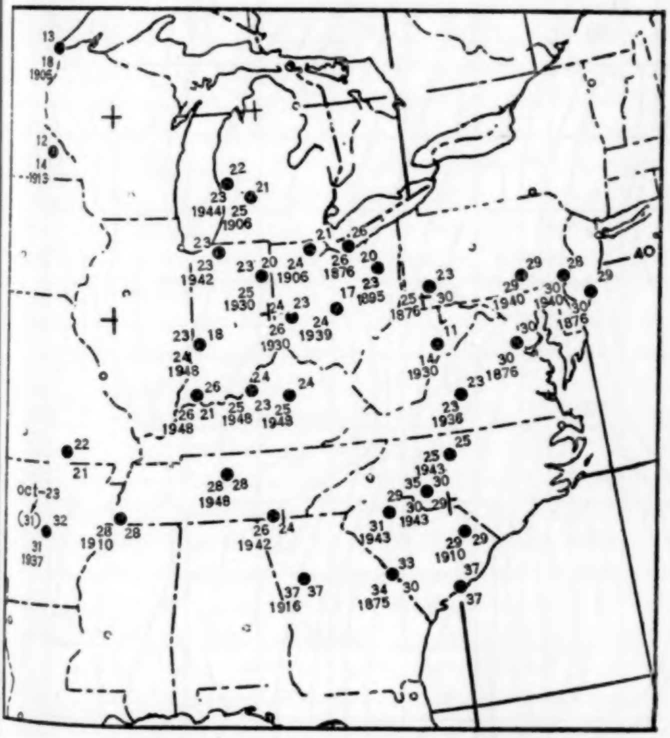

FIGURE 1.—Minimum temperatures (°F.) for selected stations in the mid-Atlantic and east central United States. Plotted figures indicate minimum for October 20, 1952 (upper left hand number), minimum for October 21 (upper right hand number), minimum for October 22 (lower right hand number), the previous record minimum for so early in the autumn and the year of occurrence (lower left hand numbers).

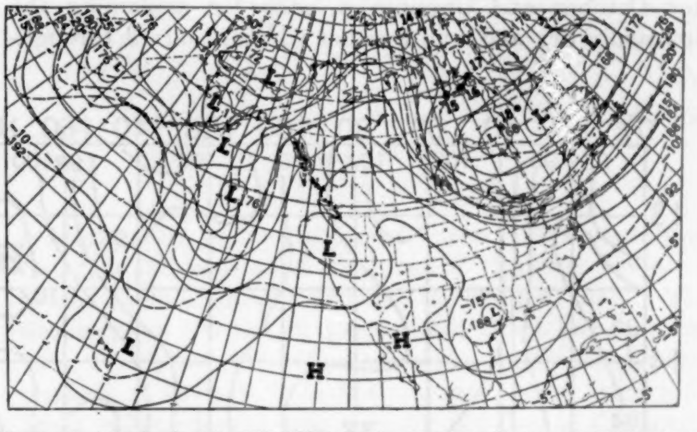

FIGURE 2.—500-mb. chart for 0300 GMT, October 19, 1952. Contours (solid lines) at 400-foot intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are drawn for intervals of 5°C. The track connects the 24-hour positions (GMT/date) of the center of the —40°C. isotherm.

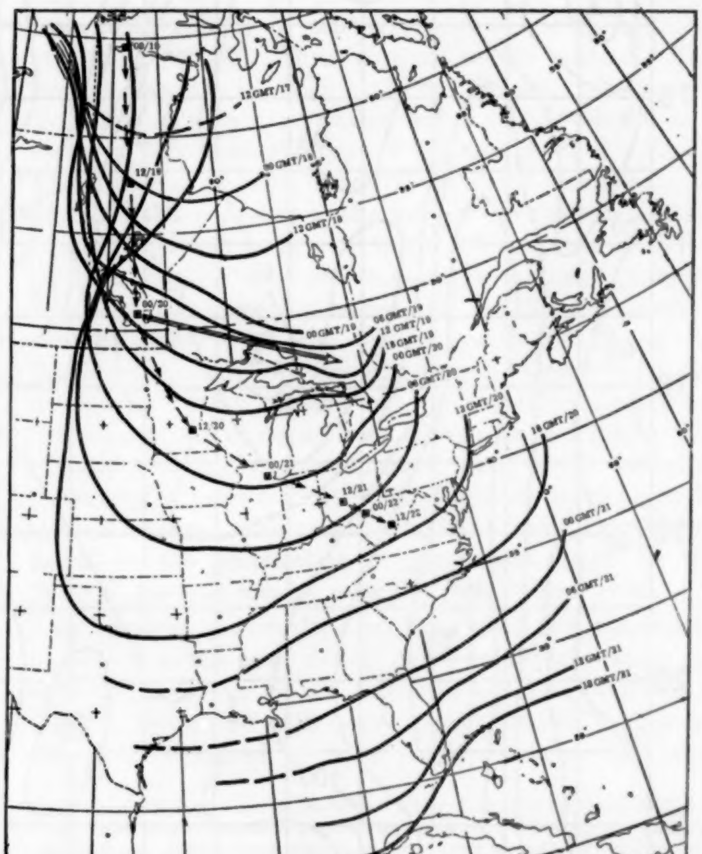

FIGURE 3.—Successive positions of the surface cold front labeled GMT/date. Track connects 12-hr. positions of the surface High center. Double shaft arrow indicates normal movement [5].

UPPER AIR CONDITIONS LEADING UP TO THE COLD WAVE

The upper air pattern which preceded this outbreak of cold air was characterized by strong northwesterly flow over the eastern part of the United States with anomalously high pressure over the Rocky Mountain area, and lower than normal pressures over the eastern United States. The dominance of this type of flow in the month's circulation pattern is shown by the mean 700-mb. charts for October and provides a basis for explaining the unusually dry and cool weather which occurred throughout the eastern half of the United States [1]. Furthermore the 5-day mean chart covering the period in which the cold outbreak took place shows a similar pattern.

Unusually cold air aloft appeared as early as October 13 over the Beaufort Sea. Figure 2, which includes the trajectory of the center of the −40° C. isotherm at 500-mb. during the period October 14–19, shows that cold air at 500-mb. moved rapidly southward from the 13th to the 15th. The cold air appeared to stagnate in the northern Hudson Bay area from October 15 through 17, but on the 18th resumed movement toward the south-southeast. By

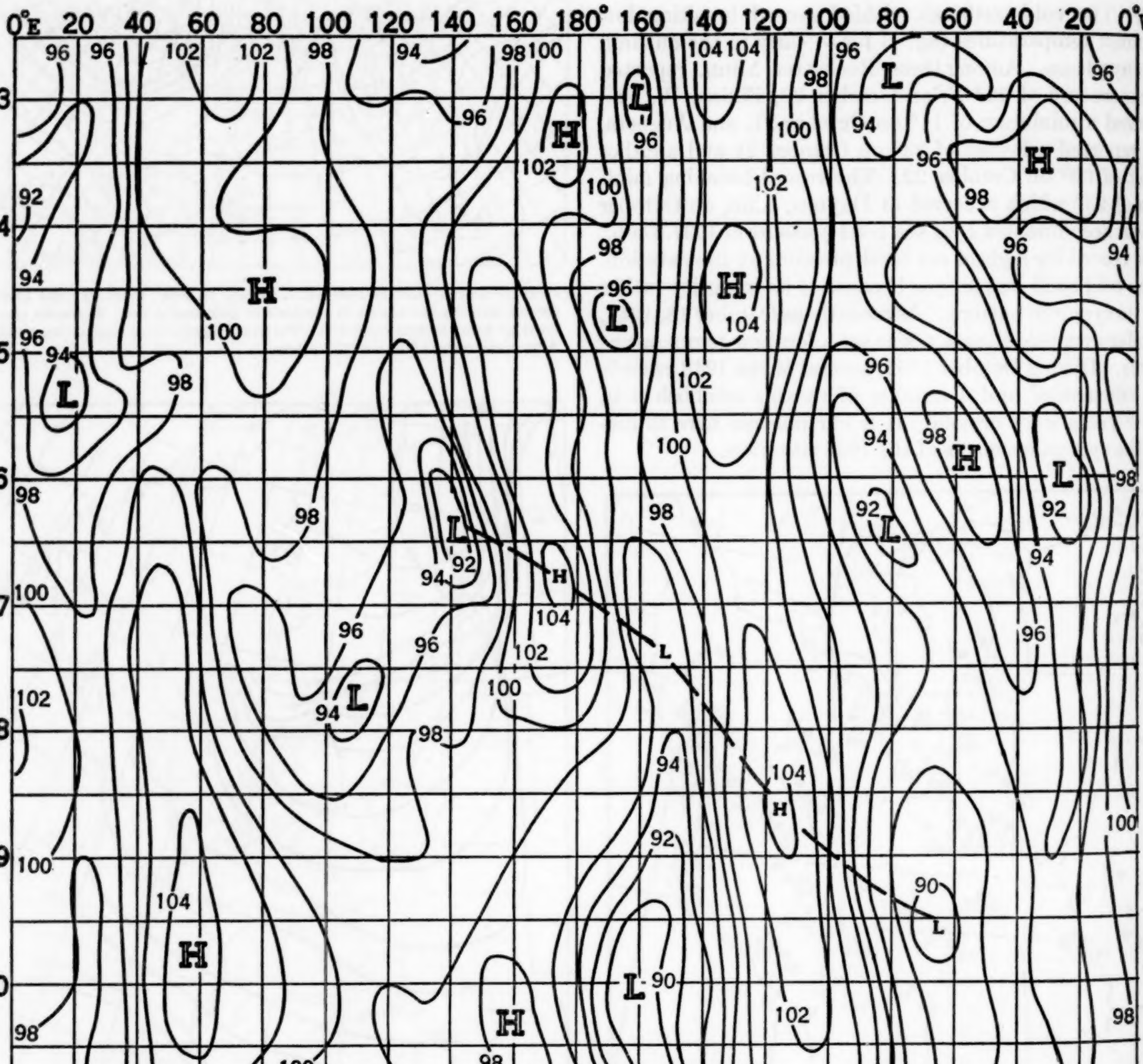

FIGURE 4.—Trough-ridge diagram showing 700-mb. heights at 50° N. lat. with ordinate in GMT date and abscissa in degrees longitude, October 13-21, 1952.

0300 GMT of the 20th the 500-mb. temperature at Sault Ste. Marie, Mich., had fallen to —40° C., or 23° C. below the normal temperature for October [2]. In spite of the general northwesterly flow into the north central United States throughout the month, this temperature was 7° C. lower than the temperature observed at this station at any other time during the month.

The trajectory of the surface High (fig. 3) was south or south-southeast during the period 0030 GMT, October 19 to 0030 GMT, October 21. In contrast to this, the more normal movement of Highs in that area [3] is east-southeastward as indicated by the double shafted arrow in the figure. This abnormal movement appears to be related to an unusually strong surge of cold air at 500-mb. which pushed southward into the eastern United States at this time. Although progress was rather halting during the early stages, this surge nonetheless became a potent factor in the synoptic situation on October 19–20 when it "steered" the High southward and set up a deep northerly current of cold air over the eastern United States.

Since the formation of the very sharp cold trough appeared to be a necessary attribute of the cold outbreak, it seemed worthwhile to investigate factors which may have been responsible for imparting an added impulse to the southward push of the cold air aloft. One such factor was suggested by the work of Rossby [4] and Yeh [5] who have discussed the transfer of atmospheric energy through dispersive waves. According to this theory the energy may travel faster than the individual waves and thus its effects, when they occur, can spread rapidly downstream. Hovmöller [6] has described a trough and ridge diagram by means of which this energy dispersal can conveniently be followed. For purposes of the present study, a modified trough-ridge diagram was constructed using 700-mb. heights at 50° N. Lat. (fig. 4). The semipermanent ridge at 115° W. is apparent and the persistent trough near 70° W. is also clearly shown. Superimposed on this pattern are the more transitory patterns. Of particular interest to the point under discussion is the series of alternate Highs and Lows connected by the dashed line on the figure. This pattern implies (1) that the formation of a deep trough at 140° E. built up a ridge at 180° some 12 hours later, (2) that the building ridge produced relatively low pressure at 150° W. some 15 hours later, (3) that this lowering of the heights at 150° W. built up pressures over the semipermanent ridge some 24 hours later and, (4) that the reinforcement of the ridge resulted in the deepening of the Low at 70° W. at 700-mb. on October 19, 0300 GMT. It must be kept in mind that this trough-ridge diagram is for latitude 50° N. only, and that the effects here discussed are not perfectly shown by such a chart. For example the Low which formed about 1500 GMT on October 17 actually formed several degrees south of the 50th parallel and therefore shows up rather imperfectly on the diagram.

Wobus and Norton [7] have studied the synoptic aspects of an energy transfer process that perhaps is somewhat

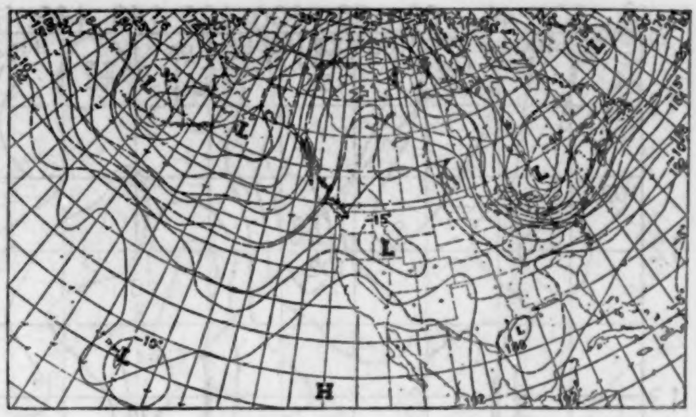

Figure 5.—500-mb. chart for 0300 GMT, October 20, 1952.

related to the process discussed above. Examination of the synoptic aspects of the present situation reveals a similar series of developments on the 500-mb. chart. The deepening of the trough north of the Great Lakes on the 20th (fig. 5) was not indicated by the approaching height changes at 500 mb. On the contrary, there were only weak 24-hour height falls of about 200 feet to the northwest of the trough at 0300 GMT on October 19. By 1500 GMT of the 20th falls of up to 600 feet had developed and were near the center of the trough. The increase in intensity of the katallobaric field seems to have resulted from rapid buildup of pressure north of 60° N. and near longitude 110° W. These rises set up the northerly flow which resulted in the "digging" [1] that deepened the trough. The rises in turn were not advected but developed as a result of the intensification of the trough in the Pacific from October 16 to 18. At 1500 GMT of October 18 the greatest rises near and to the west of the ridge in western Canada were 200 feet per 24 hours. These rises increased to more than 600 feet per 24 hours in the next 12 hours. The sequence of events as seen on the 500-mb. chart is then as follows: (1) the trough near 150° W. in the Pacific deepened, (2) this deepening strengthened the ridge over western Canada and, (3) this in turn deepened the trough over eastern United States on the 20th. The changes described above represent the synoptic aspect of the energy dispersion illustrated graphically by the trough-ridge diagram. These concepts have been found very useful in the preparation of prognostic charts in the WBAN Analysis Center over the past several years.

In connection with the conditions aloft, it is interesting to note that the most recent previous instance when the 850-mb. temperature at Nashville reached —4° C. in October (compared with —4.5° C. at 0300 GMT, October 21, 1952) occurred at 0300 GMT, October 18, 1948,

[1] The term "digging" is used in the WBAN Analysis Center to describe a situation in which winds (usually limited to winds having a northerly component) coming into an area are supergradient and as a result expend their excess kinetic energy in doing work against the pressure gradient. These winds, being deflected to their right, pile up air to their right and thus cause rising pressures there. Similarly a decrease of pressure results, to their left, in the area of "digging." This same relationship and variations of it have been described in the literature under various names (see [8, 9]).

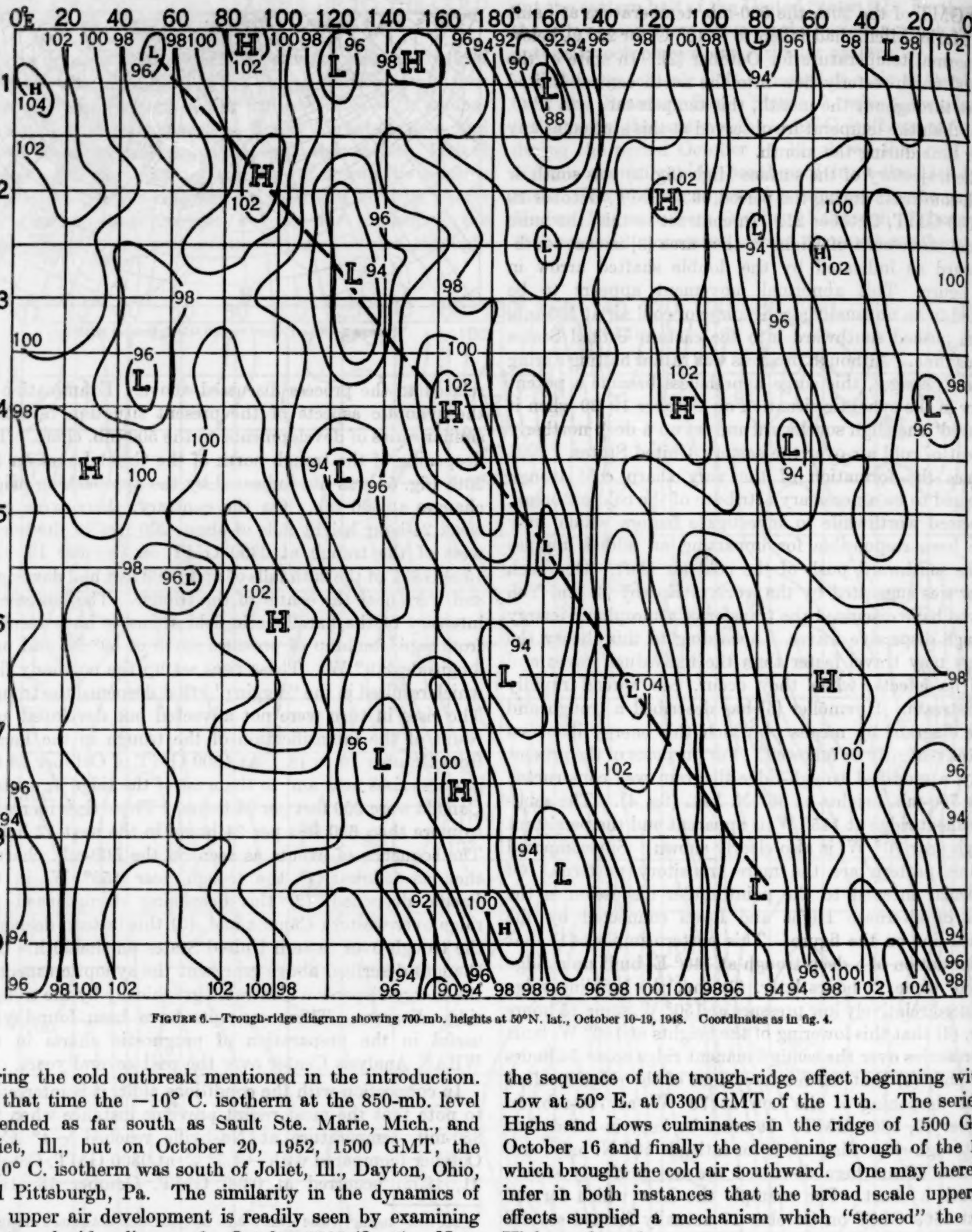

FIGURE 6.—Trough-ridge diagram showing 700-mb. heights at 50°N. lat., October 10–19, 1948. Coordinates as in fig. 4.

during the cold outbreak mentioned in the introduction. At that time the −10° C. isotherm at the 850-mb. level extended as far south as Sault Ste. Marie, Mich., and Joliet, Ill., but on October 20, 1952, 1500 GMT, the −10° C. isotherm was south of Joliet, Ill., Dayton, Ohio, and Pittsburgh, Pa. The similarity in the dynamics of the upper air development is readily seen by examining the trough-ridge diagram for October 1948 (fig. 6). Note the sequence of the trough-ridge effect beginning with a Low at 50° E. at 0300 GMT of the 11th. The series of Highs and Lows culminates in the ridge of 1500 GMT October 16 and finally the deepening trough of the 18th which brought the cold air southward. One may therefore infer in both instances that the broad scale upper air effects supplied a mechanism which "steered" the cold High southward.

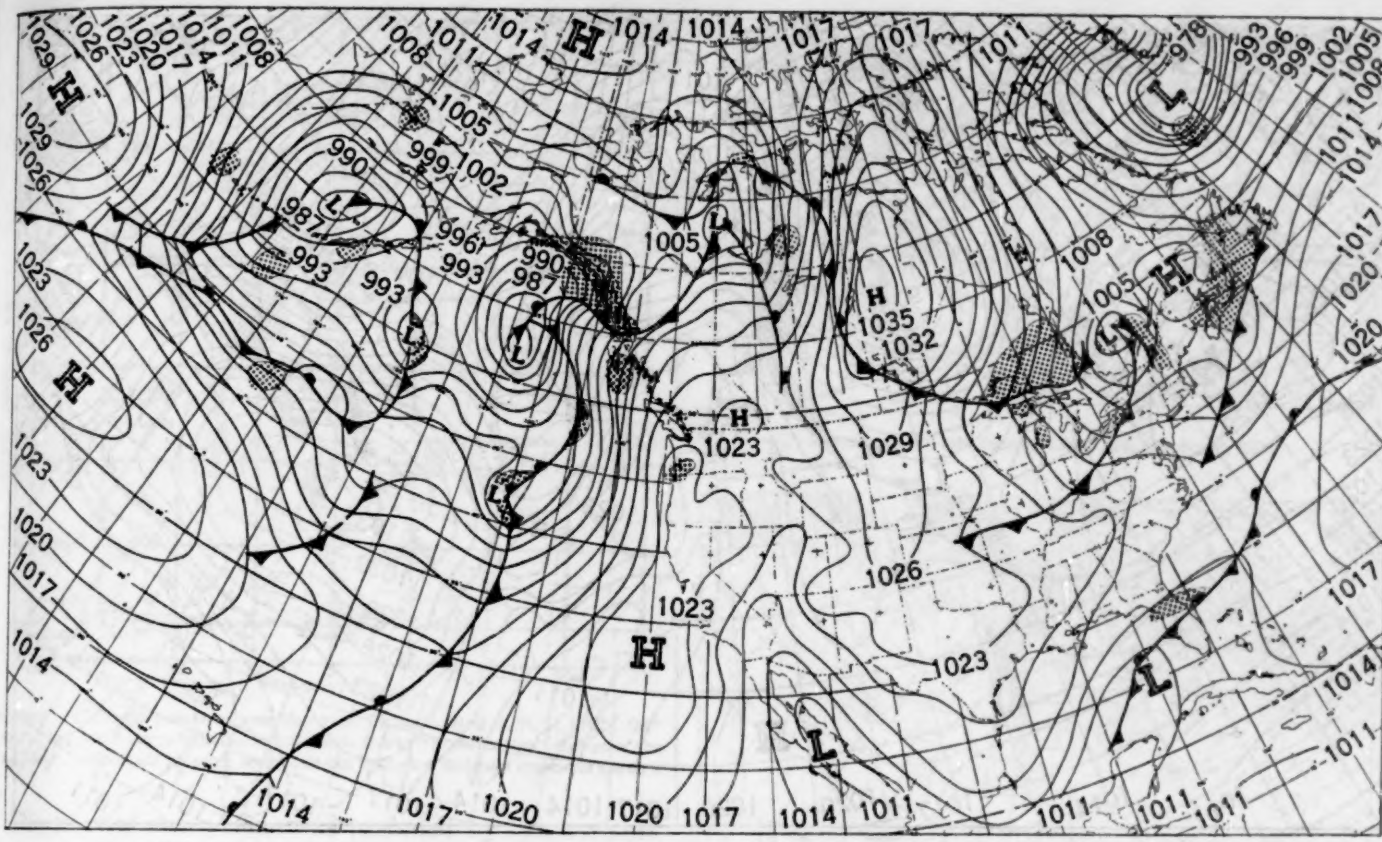

FIGURE 7.—Surface weather chart for 1230 GMT, October 19, 1952. Shading indicates areas of active precipitation. Isobars are at intervals of 3 mb.

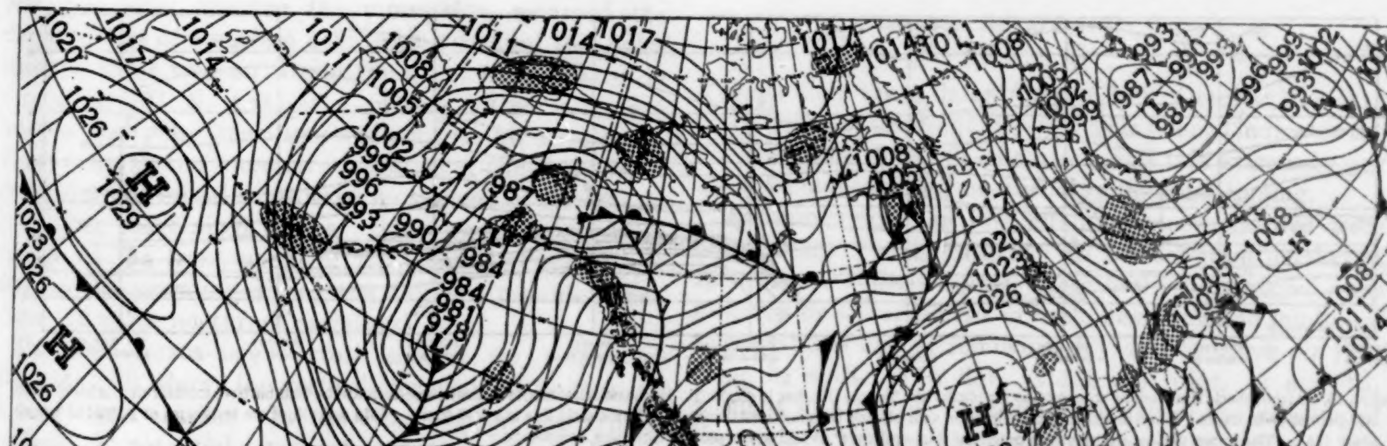

FIGURE 8.—Surface weather chart for 1230 GMT, October 20, 1952. Shading indicates areas of active precipitation.

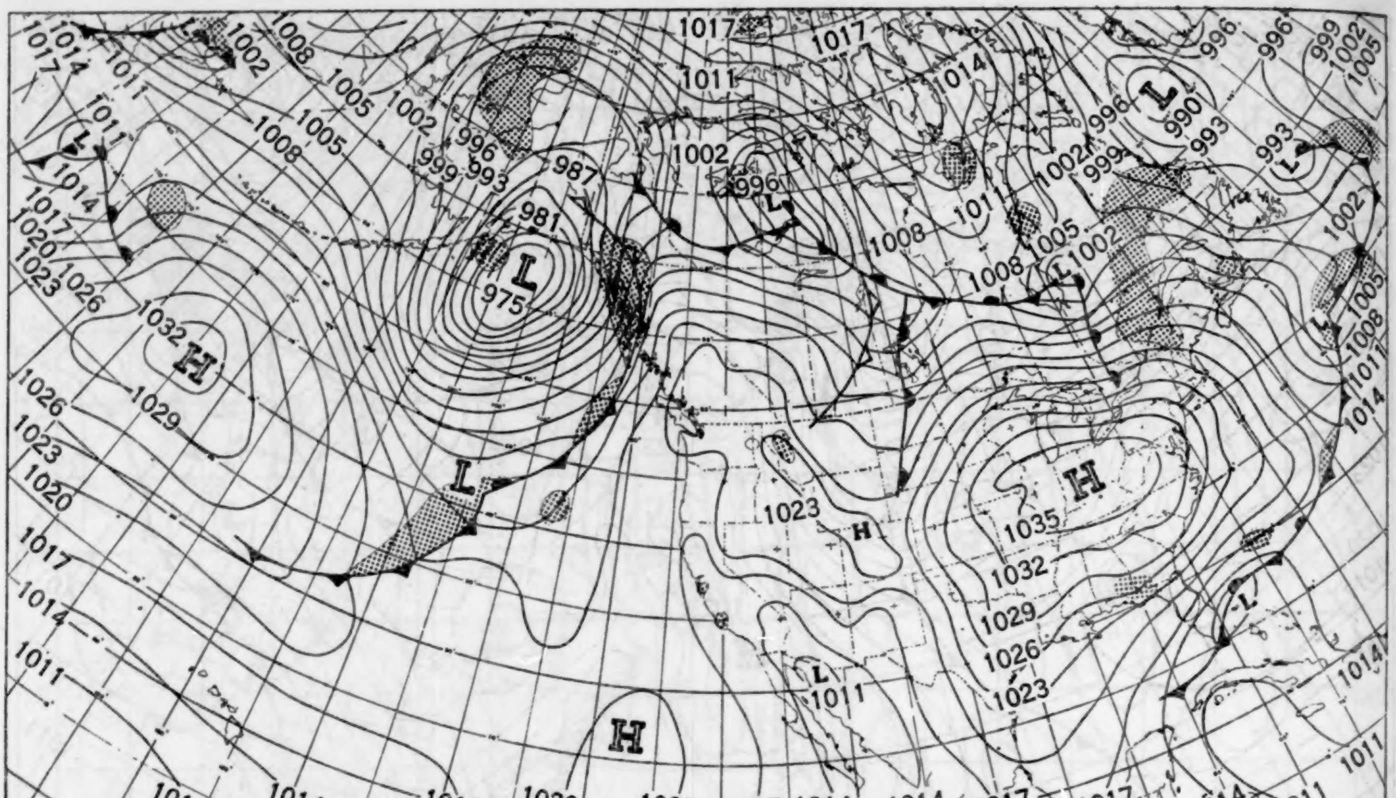

Figure 9.—Surface weather chart for 1230 GMT, October 21, 1952. Shading indicates areas of active precipitation.

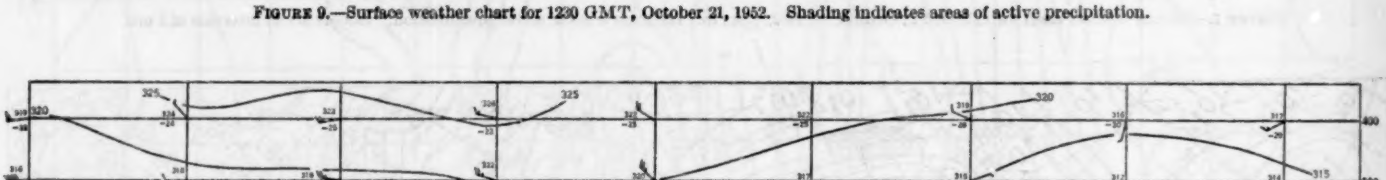

Figure 10.—Atmospheric time-height cross section for Nashville, Tenn., October 18–22, 1952. Barbs on wind shafts indicate speeds in knots; half barb=5 knots, full barb=10 knots, and pennant=50 knots. Wind shafts indicate direction as if plotted on a horizontal surface. Thick solid line is a cold front. Thin solid lines are isotherms of potential temperature (°A). The upper plotted numbers are potential temperature (°A) and lower plotted numbers, temperature (°C).

THE SURFACE CONDITIONS

The first appearance on the surface map of conditions favoring the cold outbreak was a cold anticyclone, which originated on October 18 over the area north of Hudson Bay (fig. 7). This High began to move rapidly southward bringing to eastern United States a large mass of Arctic air, which was extremely cold and extremely dry at all levels.

The High increased in intensity and reached a maximum pressure of 1041 mb. while centered near Minneapolis, Minn., 1530 GMT, October 20, 1952 (3 hours after time of fig. 8). Following this, the High continued to move southeastward, decreasing in intensity and decelerating. The center of the High remained west of the Appalachian Mountains (fig. 9) and at 1830 GMT, October 22, this High cell broke away from the westerly circulation and retrograded into Tennessee and Arkansas, where the center became diffuse.

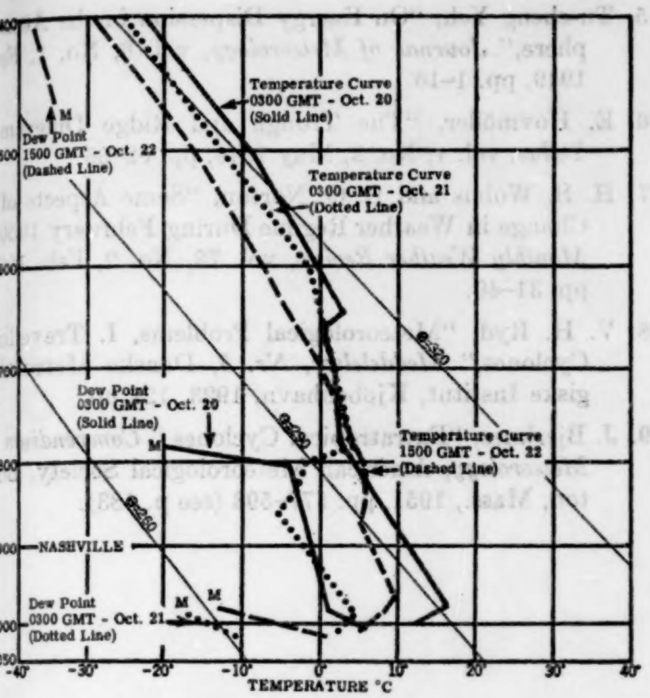

Figure 11.—Upper air soundings over Nashville, Tenn., October 20, 21, 22, 1952. "M" on the dew point curve indicates missing data due to "motorboating" (failure of the radiosonde instrument to record accurately due to the low moisture content of the air).

The intense anticyclone was preceded by two surfaces fronts (fig. 7). The first was a maritime polar front which entered the British Columbia coast as an upper cold front, but after crossing the mountains, assumed the characteristics of a surface cold front. Behind this polar maritime front was an Arctic front which originated in Canada at 60° N. Lat. as a rather diffuse boundary between the polar maritime and continental Arctic air. Figure 3 shows the successive positions of this front from the time of its initial southward movement in Canada to its leaving the United States. Snow cover, left by the passage of the front north of the Great Lakes, allowed little surface warming during the day and provided conditions ideal for nocturnal radiation.

The time-versus-height cross section for Nashville, Tenn. (fig. 10), shows the vertical structure of the front as it passed this station. In the cross section the strong gradients of potential temperature indicate the intensity of the cold front. Further evidence of the intensity of the frontal cooling is provided by figure 11, showing successive radiosonde ascents at Nashville. The intense frontal cooling in the layers below 800 mb. may be seen by comparing the soundings at 0300 GMT, October 20 and 0300 GMT, October 21. As the surface cold front moved southward into Florida (fig. 9), bringing below normal temperatures, gale force winds associated with the intense pressure gradient did considerable damage to shipping off the east coast of the State.

The Nashville soundings show that sufficient moisture was present in the air mass ahead of the front to activate the radiosonde humidity element to about 780 mb.

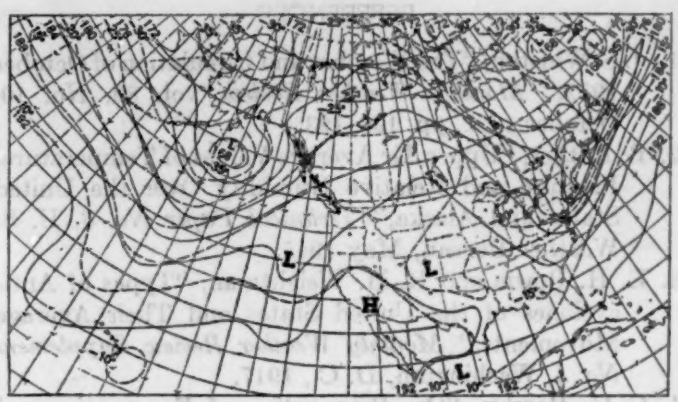

Figure 12.—500-mb. chart for 0300 GMT, October 21, 1952.

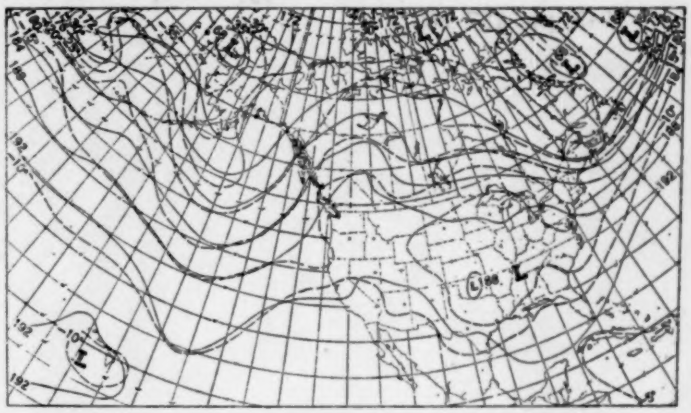

Figure 13.—500-mb. chart for 0300 GMT, October 22, 1952.

Twenty-four hours later (0300 GMT, October 21) with the passage of the front, the dew point curve indicates the air was much drier. Light winds and this extremely dry air were favorable for nocturnal radiational cooling.

Accompanying the low minimum temperatures were low maximum temperatures. In the northern portion of the eastern United States, these low temperatures were followed by a marked rise in both maximum and minimum temperatures on the following day due to warm air that came in aloft. The flow at 500 mb. (figs. 12 and 13) brought in a tongue of warm air north of the location of the surface High. This warning was in accord with the rule that the lowest minimum temperature at Washington, D. C., will usually occur the first night after the passage of the cold front. The "closed off" cold air remained over the surface High which became stagnant over the Tennessee-Arkansas area and brought a low minimum temperature of 31° F. at Little Rock, Ark., October 23, 1952, equaling the lowest so early in the autumn at this station.

CONCLUSION

The occurrence of record-breaking low temperatures October 20–22, 1952, has been related to the unique combination of upper air flow, surface pressure pattern, and ideal radiation conditions.

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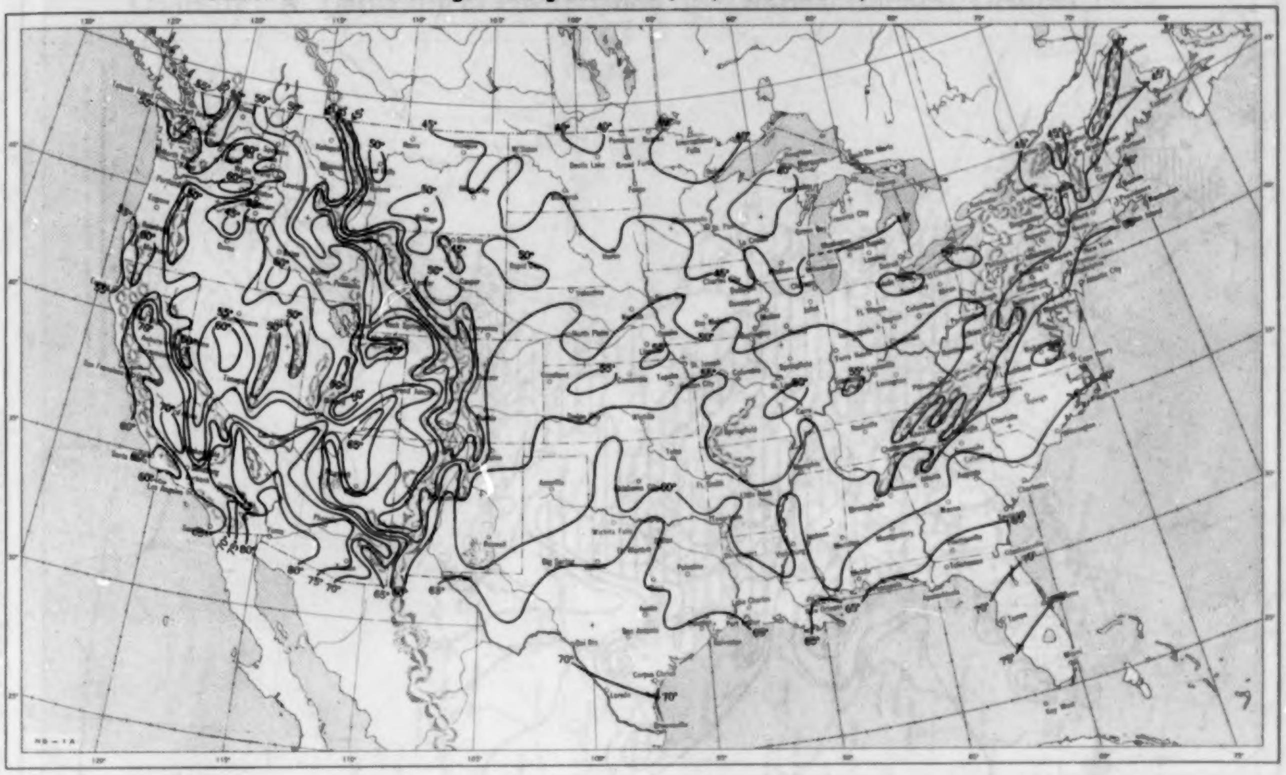
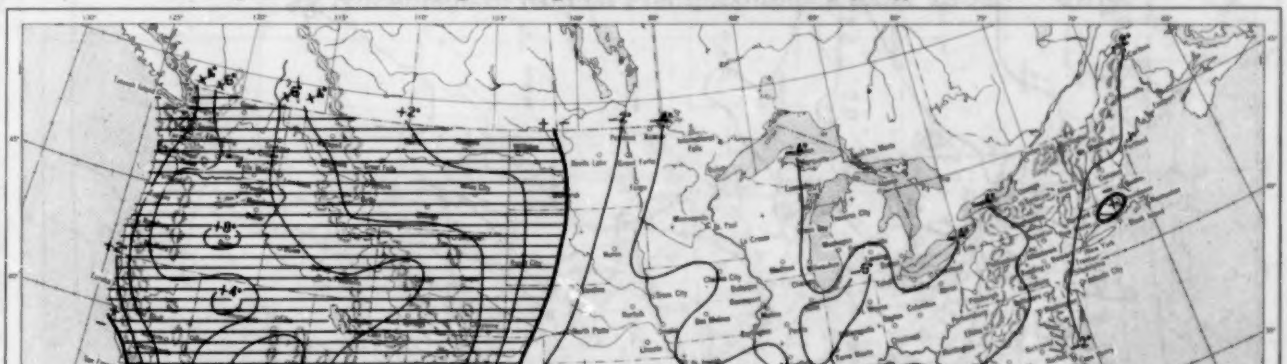
6. [illegible]
7. [illegible] Monthly Weather Review, [illegible]
8. [illegible]
9. [illegible]

Chart I. A. Average Temperature (°F.) at Surface, October 1952.

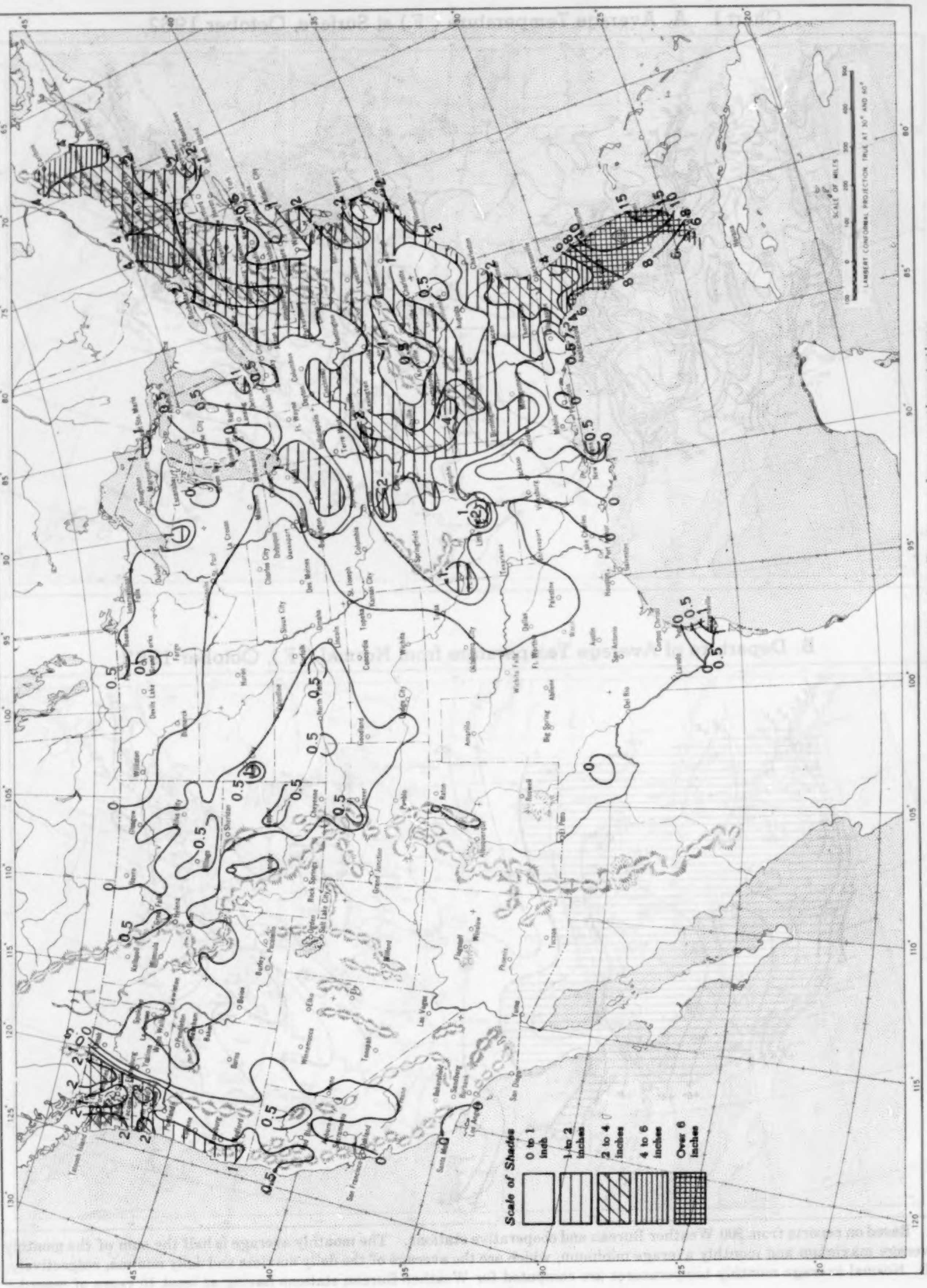


B. Departure of Average Temperature from Normal (°F.), October 1952.



A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), October 1952.



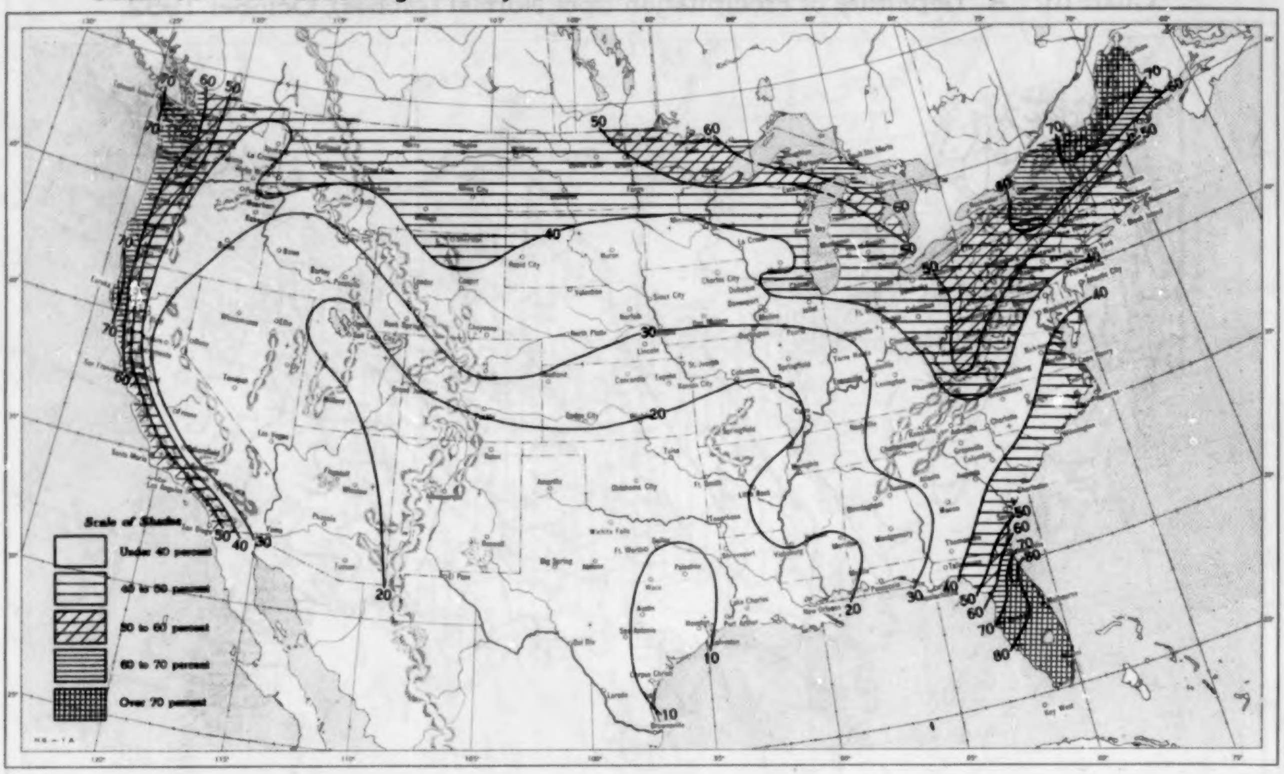
Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), October 1952.

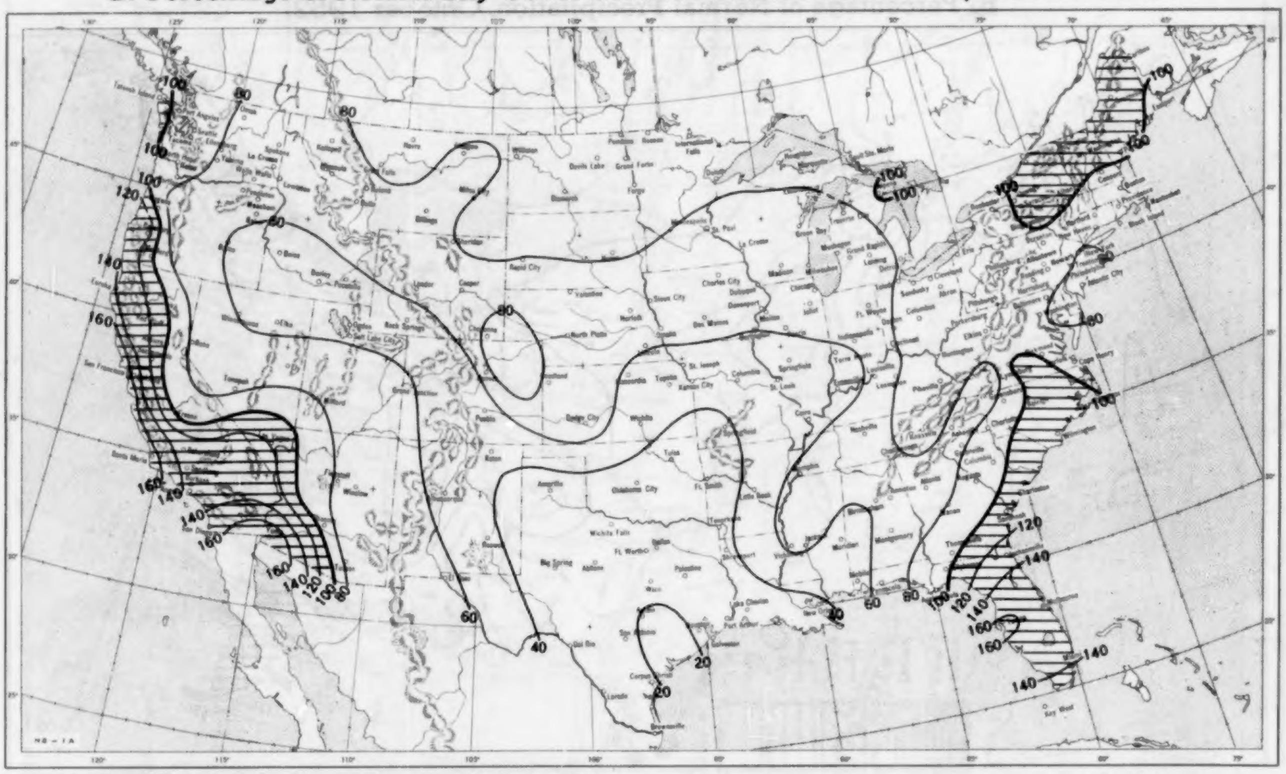
B. Percentage of Normal Precipitation, October 1952.

Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, October 1952.

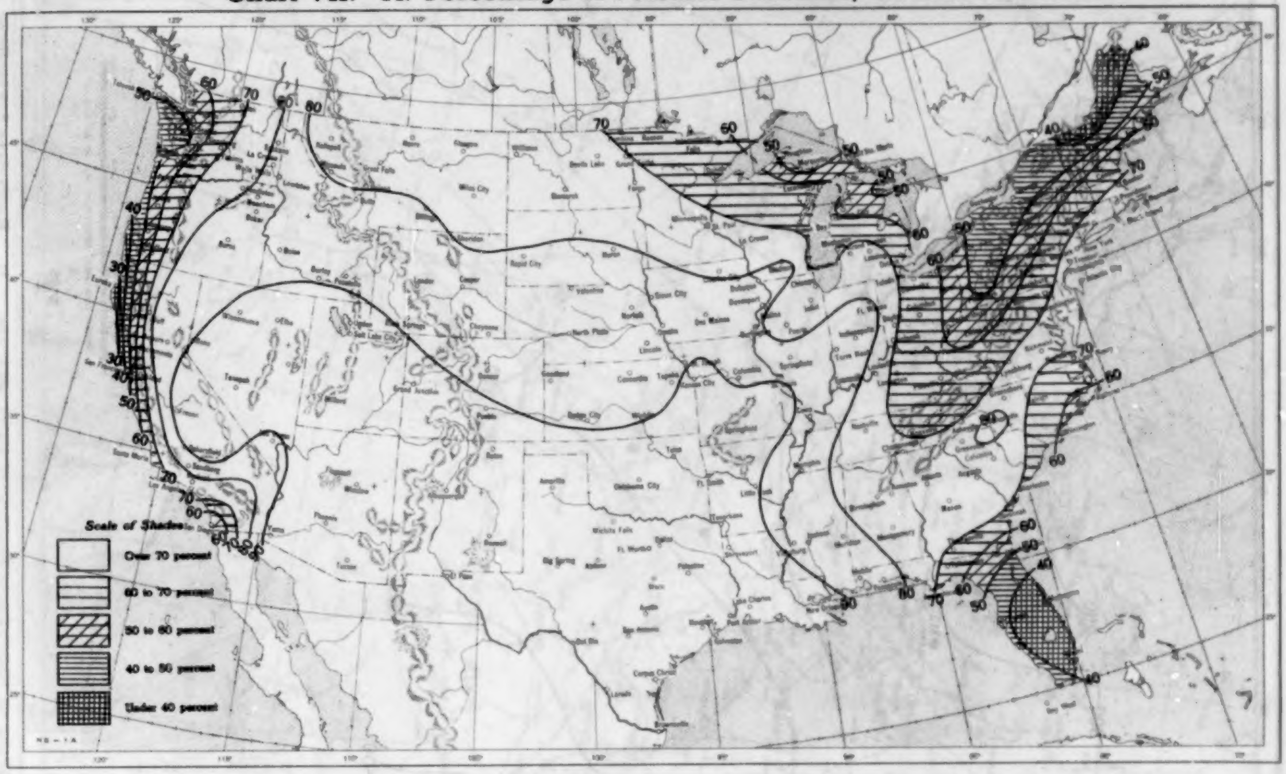


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, October 1952.

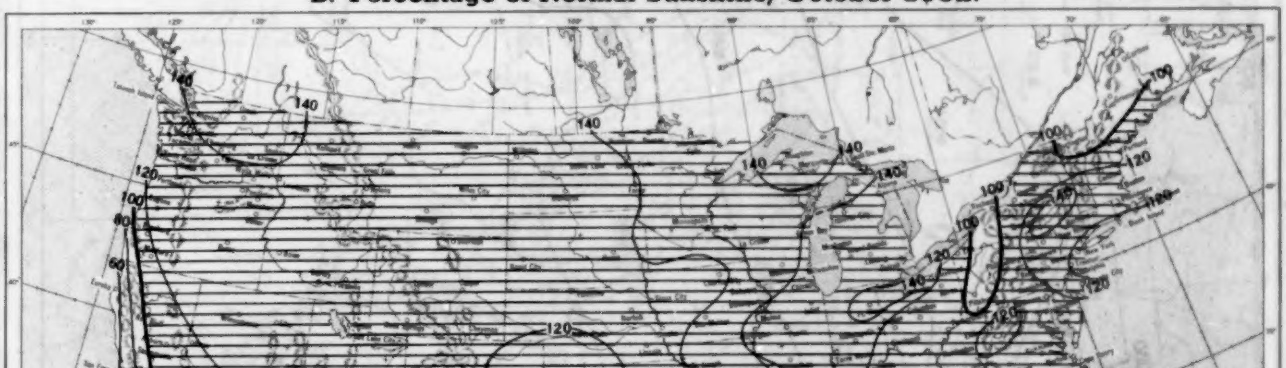


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, October 1952.



B. Percentage of Normal Sunshine, October 1952.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, October 1952. Inset: Percentage of Normal Average Daily Solar Radiation, October 1952.

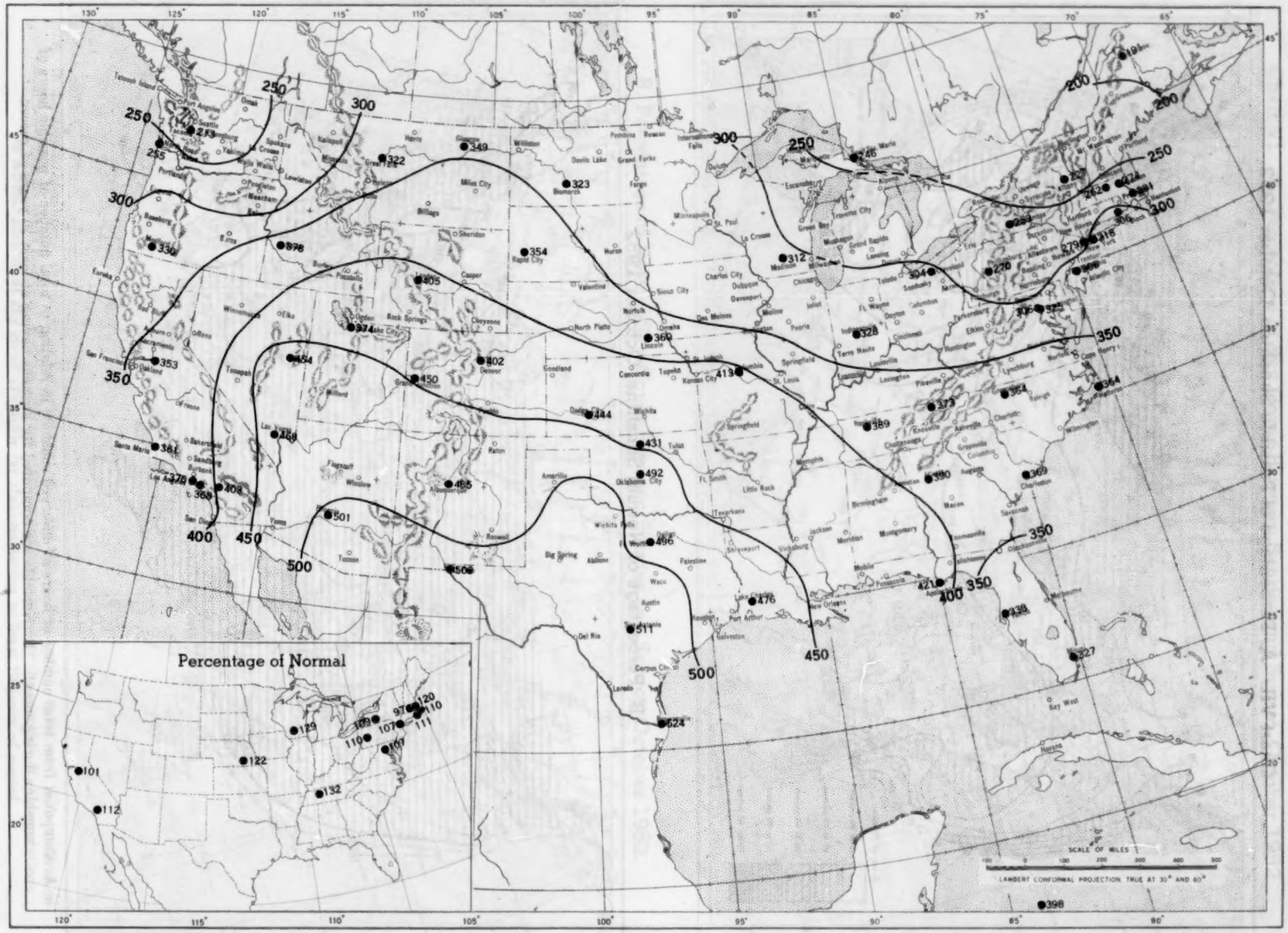
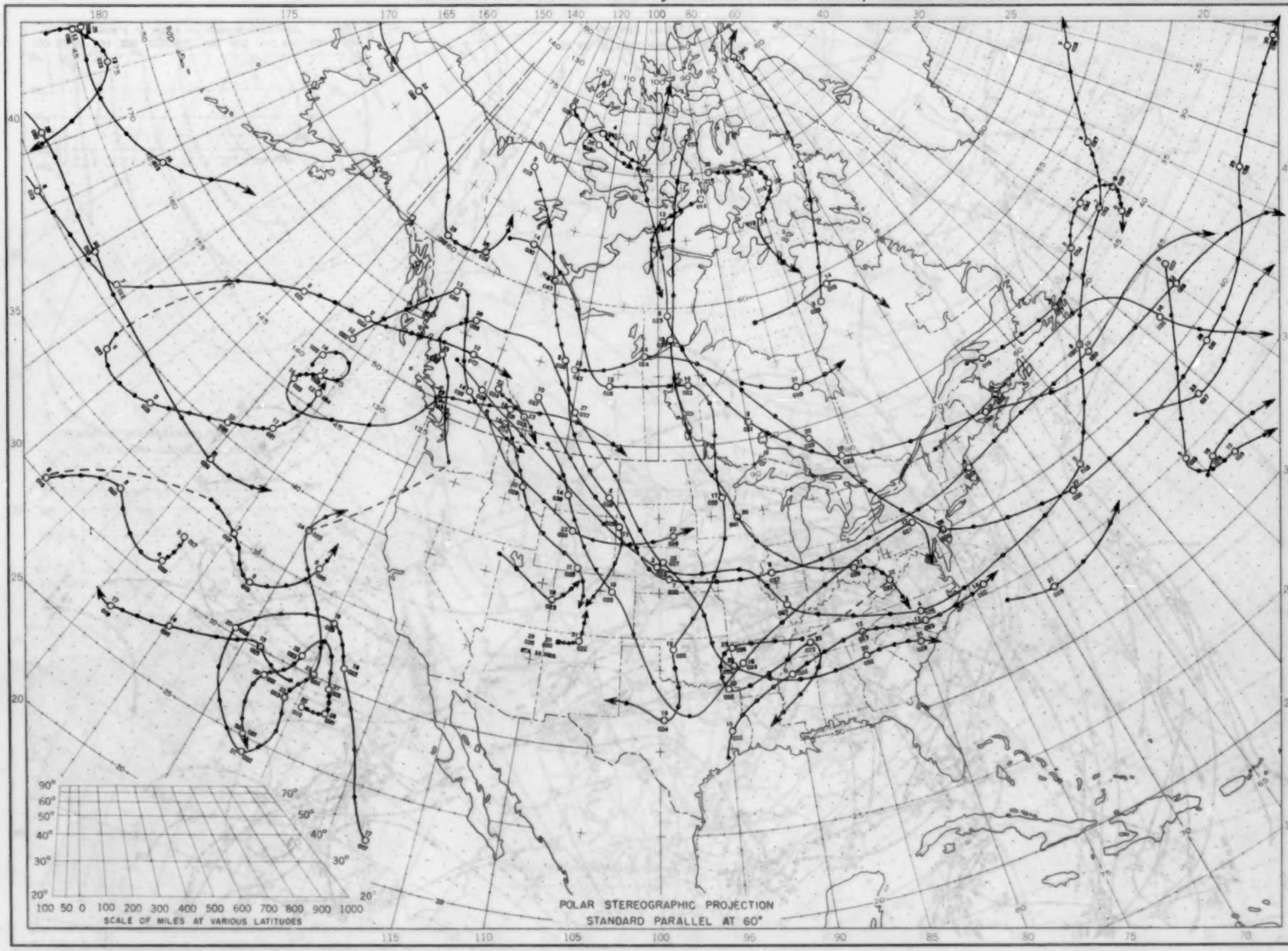


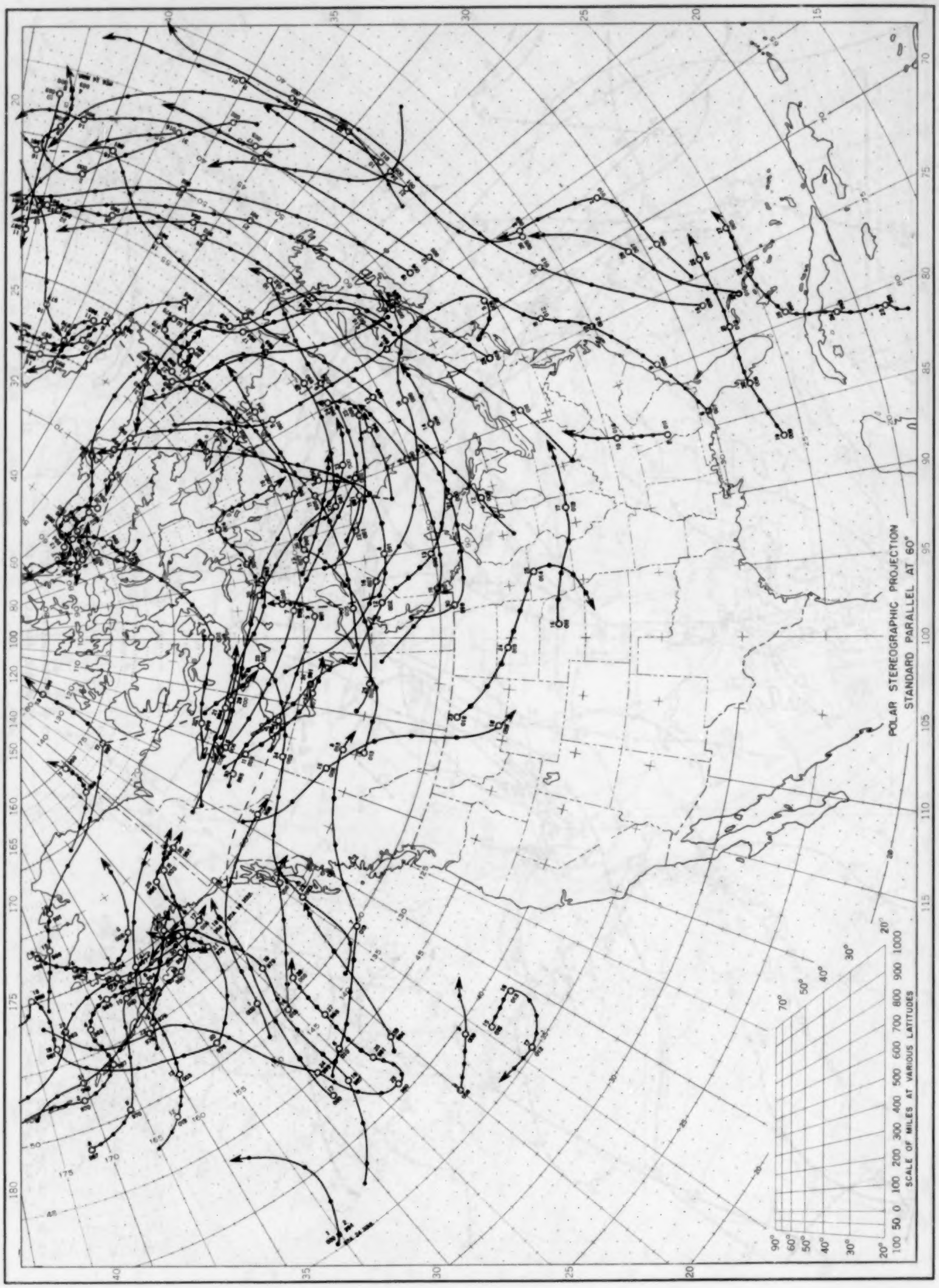
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, October 1952.



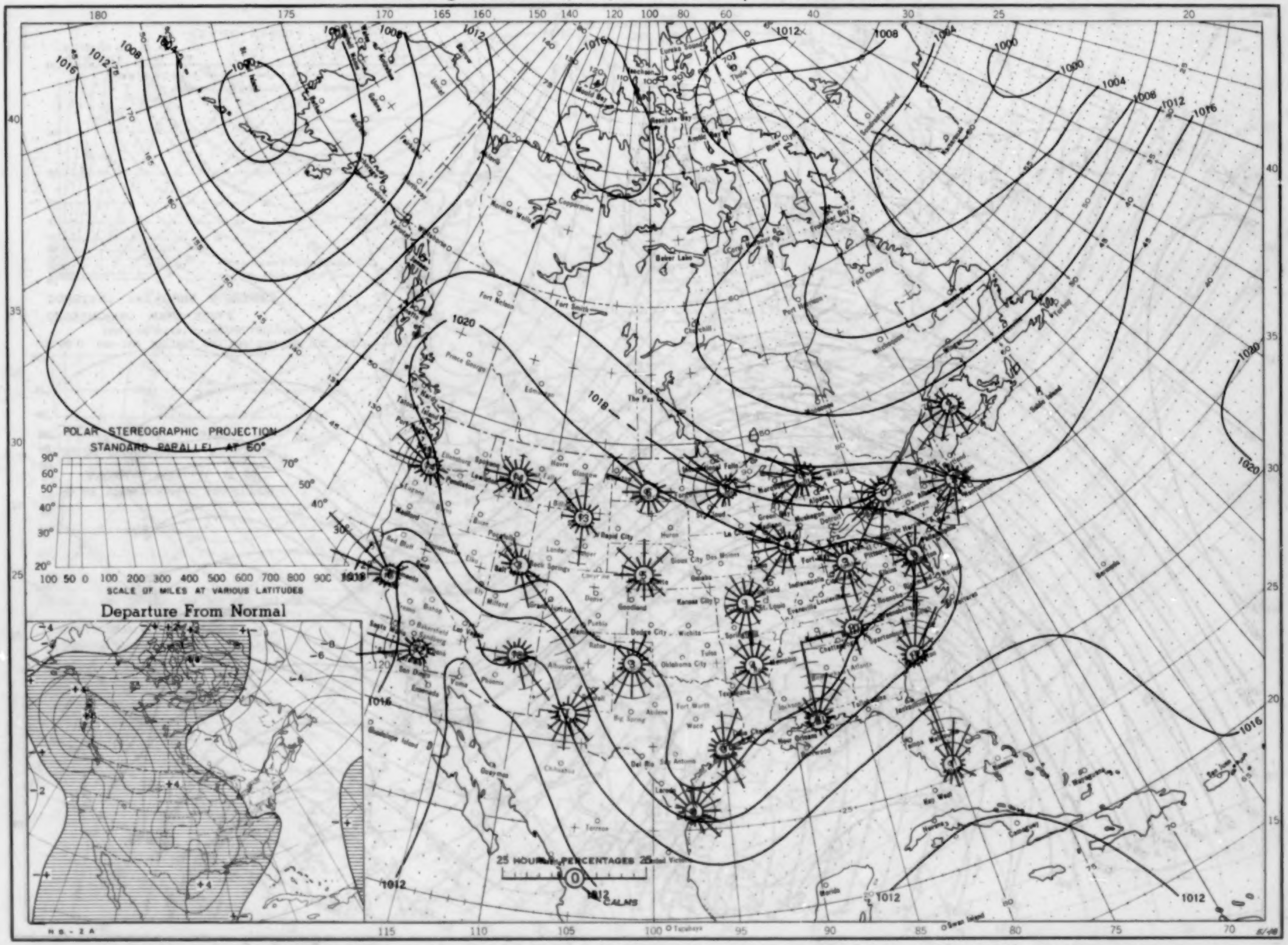
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, October 1952.



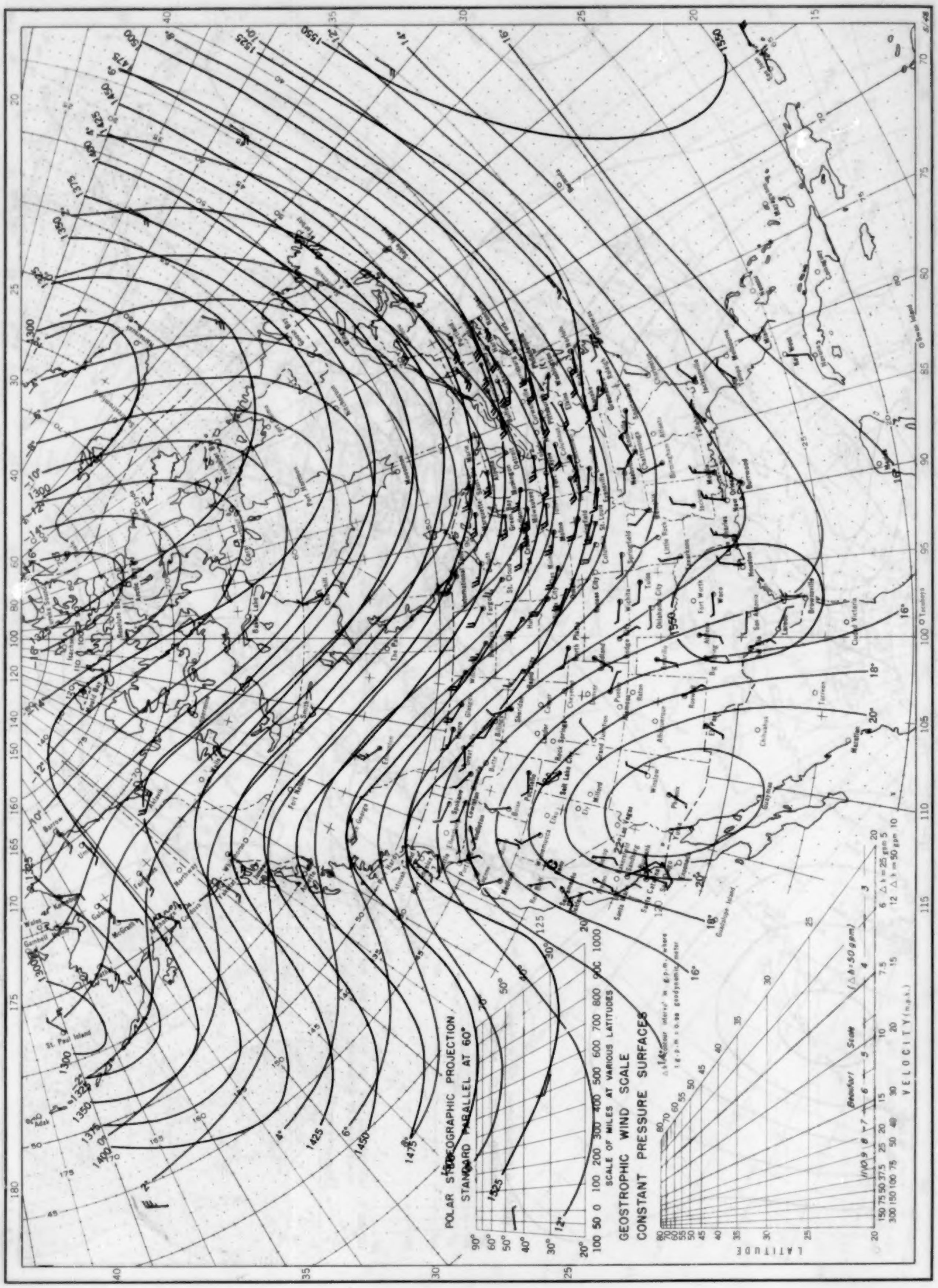
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, October 1952. Inset: Departure of Average Pressure (mb.) from Normal, October 1952.



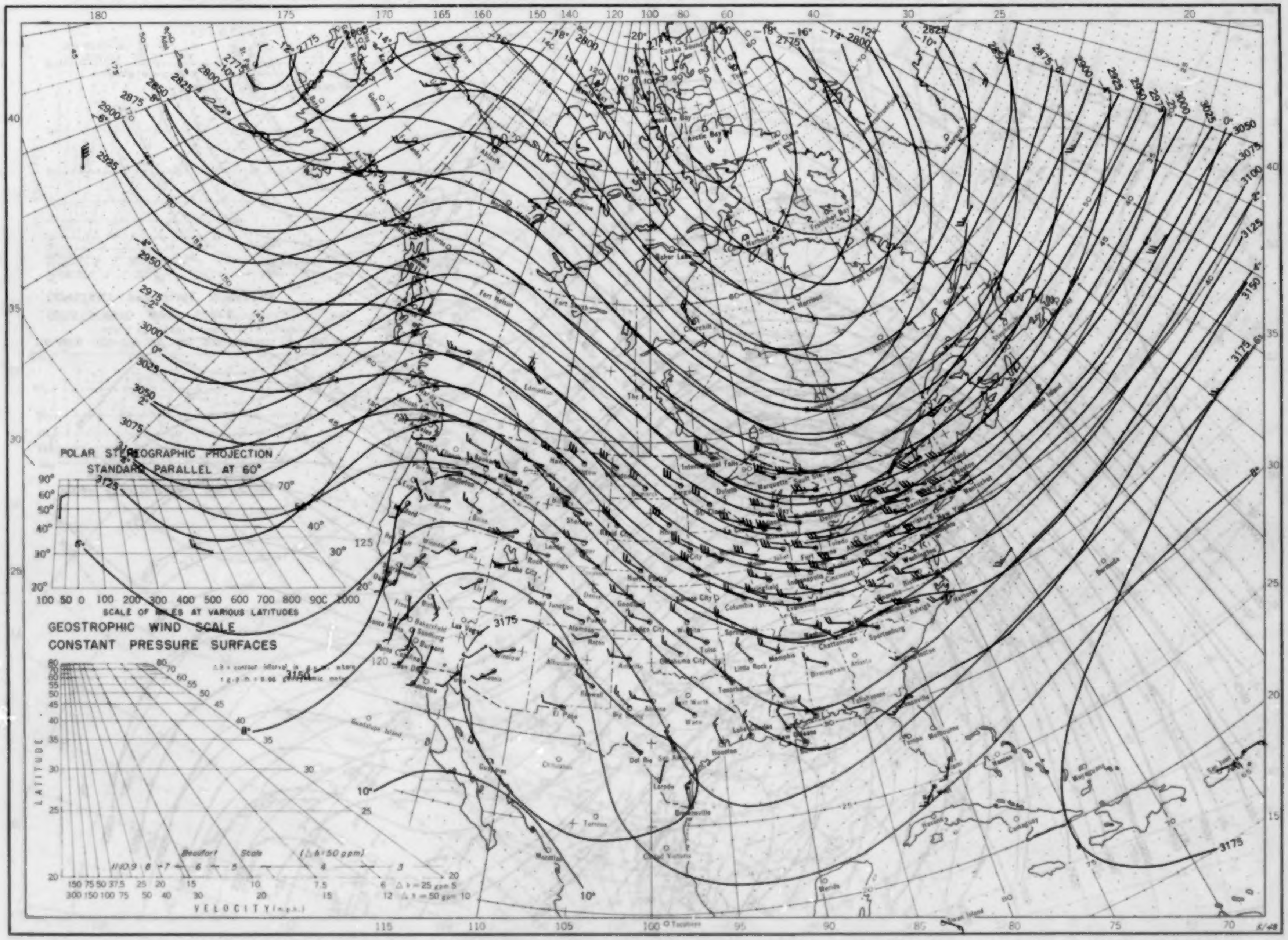
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), October 1952.



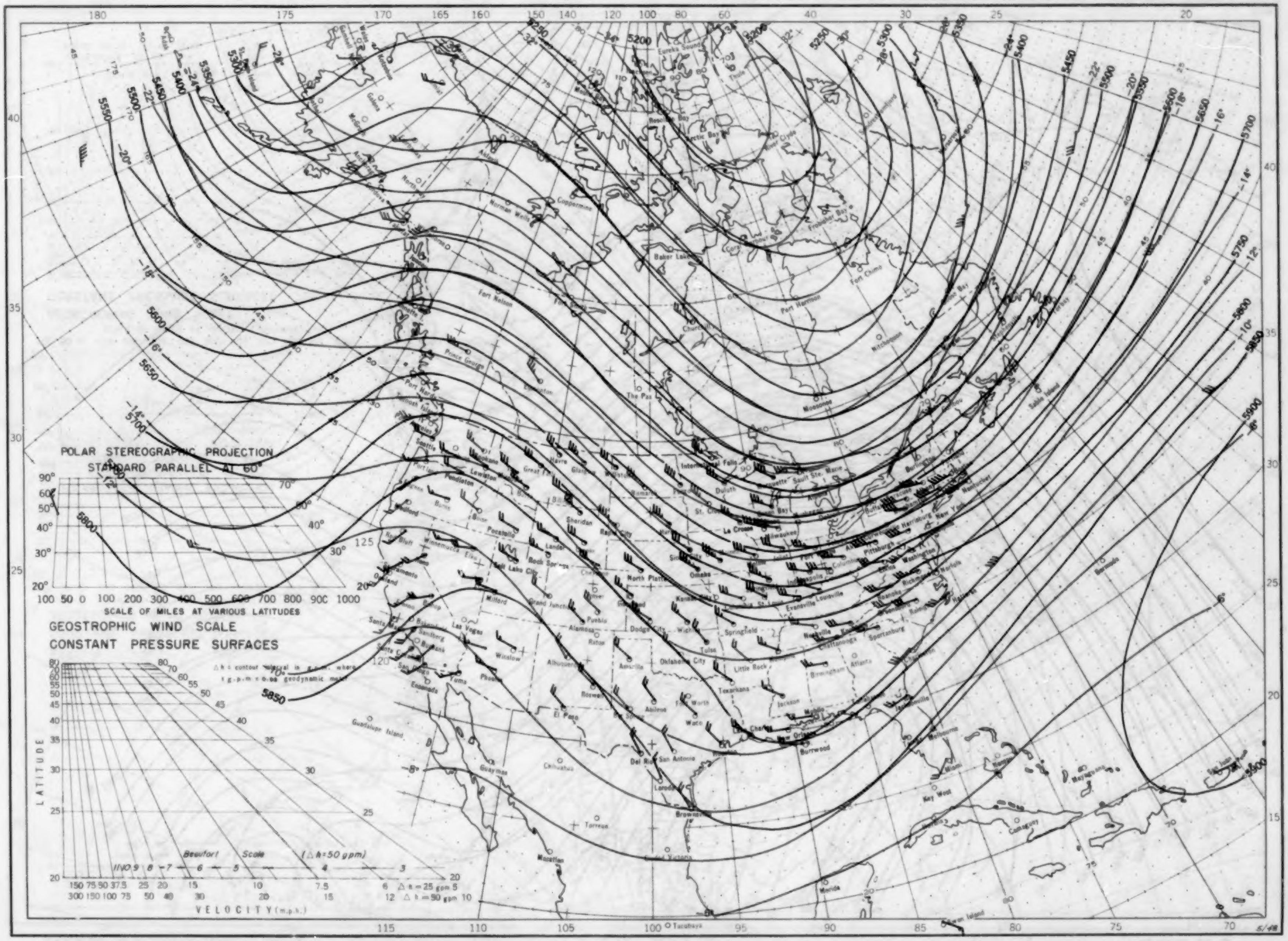
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), October 1952.



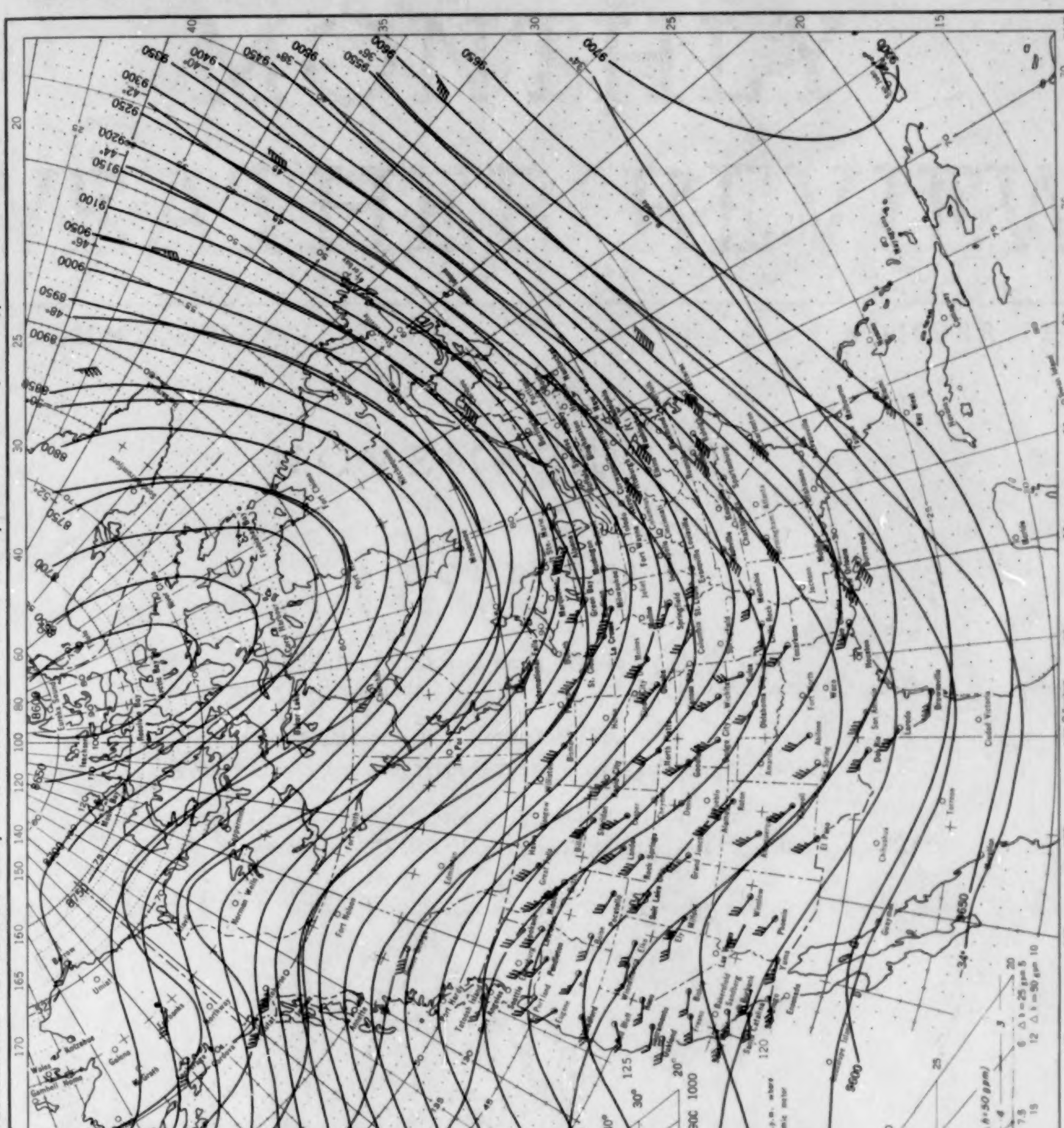
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), October 1952.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), October 1952.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.